

**GUGGENHEIM AERONAUTICAL LABORATORY**

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AN EXPERIMENTAL INVESTIGATION  
OF THE PRESSURE LOSS IN FLOW THROUGH  
HELICAL COILS

by

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PASADENA, CALIFORNIA

Thesis  
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OF THE PRESSURE LOSS IN FLOW THROUGH  
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Thesis by

Lieutenant Commander Robert A. Weatherup, USN

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### SYMBOLS

- $f$  --Friction factor for straight pipe.
- $h_c$  --Multiplicative factor by which the straight pipe friction factor is increased in order to obtain the effective friction factor for a helical coil.
- $f h_c$  --Effective friction factor for helical coil.
- $P$  --Pressure.
- $\Delta P$  --Pressure loss.
- $U$  --Mean velocity of fluid flow.
- $\dot{m}$  --Mass flow rate.
- $\rho$  --Mass density.
- $d_t$  --Inside diameter of tubing.
- $L$  --Length of tubing.
- $r$  --Internal surface roughness of the tubing. (Root mean square of surface irregularities as measured by profilometer.)
- $D_H$  --Mean diameter of the helix.
- $P_H$  --Pitch of the helix.
- $N_R$  --Reynolds number.
- $\mu$  --Absolute viscosity.

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# SUMMARY

This thesis is a report of an experimental investigation of pressure losses in flow through helical coils of circular cross section. The investigation aimed at the determination of a multiplying factor  $h_c$  which could be applied to the friction factor for an equivalent straight pipe in order to determine the effective friction factor for flow through a helical coil.

The following conclusions were reached:

1. The multiplicative factor  $h_c$  is a function of Reynolds number and has a minimum value at a Reynolds number of approximately 8,000.
2. The factor  $h_c$  is also dependent on the ratio  $\frac{D_H}{d_\tau}$ . The general effect of this ratio is to increase  $h_c$  as the ratio  $\frac{D_H}{d_\tau}$  is decreased. At Reynolds numbers above 8,000, however,  $h_c$  was found to be rather insensitive to variation in  $\frac{D_H}{d_\tau}$  over the range from  $\frac{D_H}{d_\tau} = 20$  to 30 with a minimum at  $\frac{D_H}{d_\tau} \cong 23$ .
3. The factor  $h_c$  was found to be independent of the ratios  $\frac{L}{d_\tau}$  and  $\frac{r}{d_\tau}$  over the ranges investigated.



## INTRODUCTION

Considerable literature exists relative to the computation of pressure loss in flow through straight pipes. Experiments have shown that curvature results in higher pressure loss than is predicted by the straight pipe relations. There is comparatively little literature relative to the quantitative effect of curvature on pressure loss. This is especially true in the case of turbulent flow. References 1 and 2 contain information relative to laminar flow in curved pipes. It should be noted that the ratios of friction factors given in Reference 1 are based upon the laminar flow friction factor.

This investigation was concerned with the problem of determining the pressure loss through helical coils and was limited to flow in helices formed from tubing having a circular cross section.

This investigation aimed at the determination of a multiplicative factor,  $h_c$ , which could be applied to the pressure drop computed for an equivalent straight pipe in order to obtain the pressure drop in a helical coil. A dimensional analysis which is given under the heading RESULTS AND DISCUSSION

indicated that the following dimensionless ratios were of importance in this problem:

RATIO	LIMITS OF INVESTIGATION
1. $\frac{\rho v d_{\tau}}{\mu}$ (Reynolds no.)	3,000 to 100,000
2. $\frac{D_H}{d_{\tau}}$	10.9 to 31.3
3. $\frac{L}{d_{\tau}}$	77.8 to 628.
4. $\frac{P_H}{d_{\tau}}$	Not investigated.
5. $\frac{r}{d_{\tau}}$	$4.61 \times 10^{-5}$ to $23.4 \times 10^{-5}$

This investigation was conducted at the Hydraulics Laboratory of the Jet Propulsion Laboratory, California Institute of Technology during the school year 1948--49.



EXPERIMENT

A schematic diagram of the test apparatus is shown in Fig. 1. Photographs of the test apparatus are included as Figs. 2, 3, 4 & 5. Fig. 2 is a photograph of the complete apparatus. Fig. 3 shows one of the steel helices tested. Fig. 4 shows one of the five wooden helical forms used with a plastic test specimen in place. Fig. 5 shows all five of the wooden helical forms which were used to form helices with plastic tubing. All tests were made with water as the working fluid.

Twelve helices of stainless steel were tested to determine the effect of surface roughness on  $h_c$ . These helices were practically identical except for surface roughness. The dimensions of these specimens are given in Table I. Stainless steel was selected so that the roughness would not change during the tests as a result of corrosion. Commercial stainless steel tubing was used. The interior surfaces were roughened by sand blasting. (A local firm developed a sand blasting head which was drawn through the tubing.) The specimens were tested in the straight condition and then bent and tested in the helical form. Distortion of the cross section was avoided by



filling the tubing, before bending, with a low melting point alloy known as "CERROSAP". After the alloy had solidified the tubing was bent on a cylindrical form. Then the "CERROSAP" was removed by careful steam cleaning at a temperature well above the melting point of the "CERROSAP".

The effect of the ratios  $\frac{D_H}{d_t}$  and  $\frac{L}{d_t}$  was investigated by using a plastic specimen wound on various wooden forms. The configurations of the plastic specimen as tested are given in Table II. The plastic selected had a very smooth interior. A sample of this plastic tubing was subjected to static pressure tests and showed negligible expansion under the pressures employed in this investigation.

Pressure measurements were made using a water manometer, a mercury manometer, and calibrated laboratory bourdon gages as applicable. Simultaneous pressure measurements were made on the above instruments whenever their pressure ranges overlapped. Both the water and mercury manometers were approximately twelve feet high. Gage readings were required for only a relatively few experimental points.



The test procedure involved the determination of the pressure loss at various flow rates. The pressure loss was measured on the water manometer, mercury manometer, or Bourdon tubes as applicable. The flow rate was determined by collecting the water over a suitable time interval and weighing. The temperature of the water collected was recorded from which values of viscosity and density were determined from tables in Ref. 3.

The pressure taps were located six inches from the inlet in all tests in order that the flow might be relatively uniform at the point where the pressure orifices or the taps were located. The location of the pressure taps is shown in Figs. 3 & 4. The pressure loss measured between the orifices of the pressure taps was corrected for the pressure loss in the pressure taps themselves and in the six inch leads to and from the orifices in order to obtain the pressure loss in the orifices alone. This correction was obtained by testing the pressure taps with a one foot length of tubing between them at various flow rates and plotting a curve of  $\Delta P$  vs  $\dot{m}$ . Corrections from this curve were





the following physical quantities were considered necessary to define the problem:

PHYSICAL QUANTITY	Dimensions (L = Length, T = Time)
1. Viscosity-- $\mu$	$\frac{M}{L'T}$
2. Velocity-- $v$	$\frac{L'}{T}$
3. Density-- $\rho$	$\frac{M}{(L')^3}$
4. Diameter of tube-- $d_T$	$L'$
5. Pressure loss-- $\Delta P$	$\frac{M}{L'T^2}$
6. Diameter of helix-- $D_H$	$L'$
7. Pitch of helix-- $P_H$	$L'$
8. Length of the tube-- $L$	$L'$
9. Root mean square of surface irregularities as measured by profilometer (roughness)-- $r$	$L'$

Application of dimensional analysis indicates that the following variables may be of importance in this problem:

$$1. \frac{\Delta P}{v^2 \rho} \quad (\text{Darcy's number})$$

$$2. \frac{\rho v d_t}{\mu} \quad (\text{Reynolds number})$$

$$3. \frac{L}{d_t}$$

$$4. \frac{D_H}{d_t}$$

$$5. \frac{r}{d_t}$$

$$6. \frac{P_H}{d_t}$$

The following formula for computing pressure loss in a pipe is

$$\Delta P = f \frac{L}{d_t} \frac{1}{2} \rho v^2$$

Friction factor  $f$  is known to be a function of two factors, Reynolds number and relative surface roughness.

The following formula was considered for computing

pressure loss in a pipe with corr:

$$\Delta P = h_c f \frac{L}{d_t} \frac{1}{2} \rho v^2$$

where  $h_c$  is considered to be a function of the following factors:

$$h_c = \text{function} \left( \frac{\rho v d_t}{\mu}, \frac{L}{d_t}, \frac{D_H}{d_t}, \frac{r}{d_t}, \frac{P_H}{d_t} \right)$$



The effect of Reynolds number was investigated by varying the mean velocity  $U$  while holding all other ratios constant. The effect of  $\frac{L}{d_t}$  was investigated by testing shorter and shorter lengths of the original plastic specimen. Variation of  $\frac{D_H}{d_t}$  was accomplished by winding the same specimen of plastic tubing on helical forms of various diameters. Variation of  $\frac{r}{d_t}$  was investigated over a narrow range by testing a series of twelve stainless steel helices which were practically identical except for roughness. The ratio  $\frac{P_H}{d_t}$  was not investigated. All the steel helices were tightly wound having a pitch of approximately one half inch. All of the plastic helices were wound on wooden forms which had a pitch of one inch.

The dimensions of the stainless steel specimens are given in Table I. The approximate number of turns in the helices is included in Table I as an aid in visualizing the helices although the helices are completely defined by the dimensions  $L$ ,  $P_H$  and  $D_H$ . The test results for the stainless steel specimens are tabulated in Table III and plotted in Fig. 6. Fig. 6 shows curves of the friction factor  $f$  for all of the specimens when tested in straight condition. These curves of friction factor are all very close to the friction factor curve for smooth straight pipes as given by

Moody in Ref. 4. Curves of the friction factor  $f h_c$  obtained after coiling the tubing are also given in Fig. 6. The values of  $h_c$  plotted in Fig. 6 were obtained by dividing the ordinates of the  $f h_c$  curve by the ordinates of the  $f$  curve for the same Reynolds number. Fig. 6A is a combination of certain of the  $h_c$  vs  $N_R$  curves from Fig. 6. Fig. 6B is a plot of  $h_c$  vs  $\frac{r}{d_T}$  from Fig. 6. Fig. 6C is a correlation between  $h_c$  and surface roughness. Whenever the correlation is not clear, it is  $h_c$  is a well defined function of surface roughness over the limited range investigated. The same metallurgical technique did not produce the anticipated variation in surface roughness. (The points shown in the cross plots of this report are not experimental points, but legends, indicating source of data.)

The dimensions of the plastic tubing test configurations are given in Table II. The test results are tabulated in Table IV and plotted in Figs. 7, 8, 9, 10 and 11. All of these figures show the friction factor  $f$  for the straight tubing. The friction factor  $f h_c$  for the coiled tubing is shown in a column when it was coiled into a coil on the various wooden forms. Figs. 7, 8, 9, 10 and 11 all show that  $h_c$  is a function of the Reynolds number. The similarity between Figs. 7, 8, 9, 10 and 11 can be seen if  $h_c$  is plotted against  $\frac{L}{d_T}$ . Figs. 7, 8, 9, 10 and 11 are all plotted on the same axes.



of  $h_c$  vs  $\frac{L}{d\tau}$  from the data of Figures 7, 8, 9, 10 and 11. From these cross plots,  $h_c$  does not appear to be a function of  $\frac{L}{d\tau}$  over the range investigated. This indicates that the nature of the flow in a helical coil is established rather rapidly.

Investigation of the establishment of the flow pattern at lower values of  $\frac{L}{d\tau}$  would be of interest, but a more elaborate experimental technique involving multiple pressure taps in the direction of flow would probably be required. Reference 5 contains some charts which show the nature of the flow patterns established in bends. It is interesting to note that the disturbances created by the bend are propagated for a considerable distance downstream.

Figs. 15 and 16 are cross plots of  $h_c$  vs  $\frac{D_H}{d\tau}$  from the data of Figs. 7, 8, 9, 10 and 11. Fig. 17 is a reproduction of the curves from Figs. 15 and 16. Fig. 17 shows the effect of  $\frac{D_H}{d\tau}$  upon  $h_c$  and the rather unexpected result that  $h_c$  has a minimum value at  $\frac{D_H}{d\tau} \approx 2.3$  for the higher values of Reynolds number. A somewhat similar phenomenon has been reported in Ref. 6 for 90° pipe bends.

Fig. 18 is a cross plot of  $h_c$  vs  $N_R$  from Fig. 7. Fig. 18 shows the very strong effect of Reynolds





$h_c = 12$  . . . . .

for  $\frac{L}{d\tau} = 251$  .

for  $\frac{L}{d\tau} = 77.8$  . . . . .

that  $h_c$  is independent of  $\frac{L}{d}$  at least for values of  $\frac{L}{d\tau}$  greater than  $\frac{L}{d\tau} = 77.8$  .

Either fig. 17 or fig. 18 may be used to estimate the value of  $h_c$  depending upon which is most convenient.

This investigation shows that  $h_c$  is a function of  $N_R$  and  $\frac{D_H}{d\tau}$  . The factor  $h_c$  was independent of  $\frac{L}{d\tau}$  over the range of investigation . The effect of the ratio  $\frac{P_H}{d\tau}$  was not investigated .

It is interesting to note that the values of  $h_c$  determined from the steel coils are about 10% higher than those from the plastic coils for corresponding values of  $\frac{D_H}{d\tau}$  and  $N_R$  . The curves are of the same general shape and are shown in Fig. 19 . Fig. 19 is a combination of roughly comparable test results from steel and plastic tubing . The variation of 10% is not considered unreasonable in view of the somewhat uncertain effect of variation in surface roughness and the slightly different values of the ratios  $\frac{L}{d\tau}$  and  $\frac{D_H}{d\tau}$  . It might also be noted that the steel helices had a pitch of approximately 2 inch while the plastic helices had a





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It is shown  $h_c$  is a function of time, temperature  
and  $\frac{D_H}{d\tau}$ . The diagram is in vertical,  
the combined effect of the two most important variables.

CONCLUSIONS

The following conclusions were reached as a result of this investigation:

1. The multiplicative factor  $h_c$  is a function of Reynolds number and has a minimum value at a Reynolds number of approximately 8,000. The functionality is shown in Fig. 16.

2. The factor  $h_c$  is also a function of the ratio  $\frac{D_H}{d\tau}$ . The general effect of this ratio is to increase  $h_c$  as the ratio  $\frac{D_H}{d\tau}$  is decreased. At Reynolds numbers above 8,000, however,  $h_c$  was found to be rather insensitive to variation in  $\frac{D_H}{d\tau}$  over the range from  $\frac{D_H}{d\tau} = 20$  to 30 with a minimum at  $\frac{D_H}{d\tau} \approx 23$ . The functionality is shown in Fig. 17.

3. The factor  $h_c$  was found to be independent of the ratios  $\frac{L}{d\tau}$  and  $\frac{r}{d\tau}$  over the ranges investigated.



### Recommendations

The following recommendations are submitted with regard to any further research on this problem:

1. Larger tubing, should be used in order to obtain higher values of Reynolds number.

2. The effect of surface roughness should be investigated over a greater range. The technique of sand blasting is unsatisfactory on stainless steel tubing. An attempt should be made to develop a more satisfactory method of producing surface roughness.

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1. Pressure drop  $\Delta P$ .

$$\Delta P = f \frac{L}{d_t} \frac{1}{2} \rho v^2 \quad \text{OR} \quad f = \frac{2 \Delta P d_t}{L \rho v^2}$$

2. Friction coefficient.

$$\Delta P = f h_c \frac{L}{d_t} \frac{1}{2} \rho v^2 \quad \text{OR} \quad f h_c = \frac{2 \Delta P d_t}{L \rho v^2}$$

3. Mass velocity.

$$v = \frac{4 \dot{m}}{\pi \rho d_t^2} \quad \text{OR} \quad \dot{m} = \frac{\pi d_t^2}{4} v \rho$$

4. Reynolds number.

$$N_R = \frac{\rho v d_t}{\mu}$$

TABLE I

DIMENSIONS OF STAINLESS STEEL SPECIMENS

SPECIMEN NUMBER →	1	2	3	4	5	6
L FT.	7.66	7.69	7.70	7.70	7.70	7.693
$d_r$ IN.	.470	.470	.432	.433	.438	.434
$d_r$ FT.	.0367	.0367	.0359	.0358	.0365	.0361
$r$ MICROINCHES	23.	36.	40.	29.	23.	20
$D_H$ FT.	.590	.590	.590	.590	.590	.590
$D_H/d_r$	16.06	16.06	14.22	14.27	13.75	14.10
$L/d_r$	208.5	209.0	2140	215	211.	213.
$n$ (APPROX)	4	4	4	4	4	4

SPECIMEN NUMBER →	7	8	9	10	11	12
L FT.	7.68	7.515	7.695	7.69	7.496	7.695
$d_r$ IN.	.436	.397	.432	.436	.437	.433
$d_r$ FT.	.0363	.0331	.0360	.0363	.0364	.0361
$r$ MICROINCHES	31.	93	30.	24.	21.	62
$D_H$ FT.	.585	.585	.590	.590	.585	.585
$D_H/d_r$	16.11	15.75	16.39	16.25	16.09	16.08
$L/d_r$	211.5	227.0	213.5	212.	206.	213.
$n$ (APPROX)	4	4	4	4	4	4



TABLE II

PLASTIC TUBE TEST CONFIGURATIONS

TEST NO.	1	2	3	4	5	6
L FT.	24.26	20.2	20.2	20.2	20.2	20.2
$d_t$ IN.	0.386	0.386	0.386	0.386	0.386	0.386
$d_t$ FT.	0.0322	0.0322	0.0322	0.0322	0.0322	0.0322
$D_H$ FT.	STRAIGHT	1.005	0.84	0.64	0.51	0.35
$D_H/d_t$	STRAIGHT	31.3	26.1	21.1	15.86	10.9
$L/d_t$	754.0	628.0	628.0	628.0	628.0	628.0
$n$ (approx)	0	6.5	7.7	7.6	13.0	17.5

TEST No.		7	8	9	10	11
L FT.		12.085	12.085	12.085	12.085	12.085
$d_t$ IN.		0.386	0.386	0.386	0.386	0.386
$d_t$ FT.		0.0322	0.0322	0.0322	0.0322	0.0322
$D_H$ FT.		1.005	0.84	0.64	0.51	0.35
$D_H/d_t$		31.3	26.1	21.1	15.86	10.9
$L/d_t$		375.0	375.0	375.0	375.0	375.0
$n$ (approx.)		3.7	4.7	5.7	7.7	11.7

TEST No.		12	13	14	15	16
L FT.		8.065	8.065	8.065	8.065	8.065
$d_t$ IN.		0.386	0.386	0.386	0.386	0.386
$d_t$ FT.		0.0322	0.0322	0.0322	0.0322	0.0322
$D_H$ FT.		1.005	0.84	0.64	0.51	0.35
$D_H/d_t$		31.3	26.1	21.1	15.86	10.9
$L/d_t$		251.0	251.0	251.0	251.0	251.0
$n$ (approx.)		2.6	3.0	4.0	5.1	7.7

# TABLE II

PLASTIC TUBE TEST CONFIRMATION

TEST No.	17	18	19	20	21	
L FT.	5.555	5.555	5.555	5.555	5.555	
d <sub>t</sub> IN.	0.386	0.386	0.386	0.386	0.386	
d <sub>t</sub> FT.	0.0322	0.0322	0.0322	0.0322	0.0322	
D <sub>H</sub> FT.	1.005	0.84	0.64	0.51	0.35	
D <sub>H</sub> /d <sub>t</sub>	31.3	26.1	21.1	15.86	10.7	
L/d <sub>t</sub>	172.5	172.5	172.5	172.5	172.5	
n (approx.)	1.7	2.1	2.6	3.5	5.2	

TEST No.	22	23	24	25	26	
L FT.	2.505	2.505	2.505	2.505	2.505	
d <sub>t</sub> IN.	0.386	0.386	0.386	0.386	0.386	
d <sub>t</sub> FT.	0.0322	0.0322	0.0322	0.0322	0.0322	
D <sub>H</sub> FT.	1.005	0.84	0.64	0.51	0.35	
D <sub>H</sub> /d <sub>t</sub>	31.3	26.1	21.1	15.86	10.9	
L/d <sub>t</sub>	77.8	77.8	77.8	77.8	77.8	
n (approx.)	0.8	1.0	1.1	1.5	2.2	



## TABLE III

## STEEL TUBING TEST RESULTS

SPECIMEN No. 1 - STRAIGHT				SPECIMEN No. 1 - COILED			
$P = 1.756 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.21 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.42 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f_{hc}$
9.7	0.00219	3,450	0.0416	11.7	0.00176	2,525	0.0778
15.7	0.00292	4,590	0.0387	29.6	0.00341	4,870	0.1524
31.2	0.00424	6,660	0.0361	42.3	0.00436	6,250	0.0458
43.2	0.00511	8,040	0.0341	55.5	0.00523	7,500	0.0418
102.0	0.00845	13,250	0.0297	93.4	0.00712	10,220	0.0378
226.0	0.0133	20,900	0.0263	224.5	0.0114	16,370	0.0355
374.0	0.0176	27,700	0.0249	406.0	0.0158	22,750	0.0333
627.0	0.0238	37,400	0.0229	677.0	0.0212	30,400	0.0310
1148.0	0.0337	52,900	0.0209	1297.0	0.0302	43,200	0.0294
2990.0	0.0578	90,900	0.0185	2385.0	0.0423	66,700	0.0275
5290.0	0.0791	124,100	0.0175	5370.0	0.0665	95,300	0.0250
6640.0	0.0894	146,400	0.0172	7420.0	0.0784	112,300	0.0248

SPECIMEN No. 2 - STRAIGHT				SPECIMEN No. 2 - COILED			
$P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.21 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f_{hc}$
18.0	0.00301	4,730	0.0408	20.4	0.00272	4,160	0.0568
27.1	0.00389	6,110	0.0368	131.8	0.00867	12,920	0.0612
42.7	0.00504	7,890	0.0348	426.0	0.0165	24,660	0.0317
53.1	0.00576	9,040	0.0328	838.0	0.0243	30,200	0.0293
92.3	0.00798	12,530	0.0298	2490.0	0.0448	66,800	0.0256
201.0	0.01248	19,620	0.0265	5010.0	0.0659	98,200	0.0238
354.0	0.0172	27,100	0.0244				
616.0	0.0236	37,100	0.0227				
1144.0	0.0333	52,400	0.0212				
2075.0	0.0473	74,500	0.0190				
4340.0	0.0713	112,000	0.0176				
5150.0	0.0790	124,100	0.0170				



TABLE III CONT'D.  
STEEL TUBING TEST RESULTS

SPECIMEN No. 3 - STRAIGHT				SPECIMEN No. 3 - COILED			
$P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.21 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS./FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f$	$\Delta P$ LBS./FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$
26.1	0.00316	5,660	0.0377	13.7	0.00204	3,110	0.0616
32.7	0.00413	6,580	0.0362	30.6	0.00339	5,150	0.0498
44.1	0.00484	7,750	0.0353	55.0	0.00505	7,720	0.0402
87.4	0.00728	11,660	0.0307	93.9	0.00687	10,480	0.0373
214.0	0.01232	19,750	0.0263	428.0	0.0159	24,200	0.0317
376.0	0.0169	27,100	0.0245	1267.0	0.0291	44,400	0.0280
646.0	0.0229	36,700	0.0231	2355.0	0.0412	62,800	0.0260
1183.0	0.0325	52,100	0.0210	7660.0	0.0783	119,400	0.0234
2140.0	0.0457	73,100	0.0192				
4516.0	0.0693	110,800	0.0176				
5156.0	0.0793	126,800	0.0168				

SPECIMEN No. 4 - STRAIGHT				SPECIMEN No. 4 - COILED			
$P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.21 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS./FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f$	$\Delta P$ LBS./FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$
12.2	0.00237	3,780	0.0416	12.6	0.00179	2,710	0.0759
26.2	0.00387	6,170	0.0332	28.7	0.00332	5,040	0.0495
38.7	0.00469	7,360	0.0346	63.4	0.00559	8,470	0.0386
52.4	0.00553	8,810	0.0326	99.6	0.00724	10,950	0.0362
51.8	0.00715	11,400	0.0305	330.0	0.0140	21,200	0.0322
208.0	0.0119	18,970	0.0280	1260.0	0.0296	44,700	0.0273
344.0	0.0165	26,300	0.0241	4540.0	0.0605	91,800	0.0236
630.0	0.0230	36,600	0.0228	7360.0	0.0782	118,600	0.0229
1180.0	0.0341	54,400	0.0194				
2150.0	0.0466	74,300	0.0189				
4480.0	0.0700	111,700	0.0174				
5570.0	0.0786	125,400	0.0172				

TABLE III CONT'D.  
STEEL TUBING TEST RESULTS

SPECIMEN No. 5 - STRAIGHT				SPECIMEN No. 5 - COILED			
$P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f_{hc}$
15.6	0.01284	4,250	0.0390	14.4	0.00191	2,860	0.0794
36.6	0.00447	6,700	0.0368	32.6	0.00358	5,350	0.0513
79.5	0.00733	10,990	0.0299	50.8	0.00497	7,440	0.0414
389.0	0.0178	26,600	0.0198	94.6	0.00720	10,780	0.0369
1163.0	0.0335	50,100	0.0209	411.0	0.0161	24,050	0.0321
4910.0	0.0736	110,300	0.0182	1267.0	0.0303	45,400	0.0278
				2335.0	0.0422	63,200	0.0264
				7225.0	0.0787	117,800	0.0235

SPECIMEN No. 6 - STRAIGHT				SPECIMEN No. 6 - COILED			
$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.42 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f_{hc}$
16.0	0.00277	4,040	0.0399	13.9	0.00193	2,920	0.0715
33.4	0.00426	6,200	0.0354	31.9	0.00388	5,860	0.0408
88.3	0.00734	10,680	0.0315	51.0	0.00501	7,570	0.0391
333.0	0.0158	23,100	0.0254	92.9	0.00697	10,510	0.0367
1138.0	0.0337	49,100	0.0193	426.0	0.0161	24,400	0.0314
5140.0	0.0736	107,200	0.0182	1274.0	0.0297	44,800	0.0278
				2370.0	0.0417	63,000	0.0261
				7600.0	0.0780	117,800	0.0240



TABLE III CONT'D  
STEEL TUBING TEST RESULTS

SPECIMEN No. 7 - STRAIGHT				SPECIMEN No. 7 - COILED			
$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 0.42 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f h_c$
12.4	0.00234	3,390	0.0449	10.9	0.00157	2,360	0.0815
46.2	0.00501	7,240	0.0365	32.2	0.00361	5,430	0.0469
97.9	0.00775	11,190	0.0322	47.4	0.00485	7,270	0.0415
346.0	0.01597	23,100	0.0269	434.0	0.0165	24,750	0.0316
1315.0	0.0353	51,100	0.0209	1272.0	0.0300	45,200	0.0279
4970.0	0.0737	106,500	0.0182	2335.0	0.0418	62,800	0.0265
				5380.0	0.0664	99,800	0.0241
				7350.0	0.0781	117,200	0.0239

SPECIMEN No. 8 - STRAIGHT				SPECIMEN No. 8 - COILED			
$P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.931 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.35 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re_{NR}$	$f h_c$
22.3	0.00263	4,360	0.0405	13.5	0.00144	2,360	0.0810
30.5	0.00317	5,250	0.0380	25.2	0.00230	3,780	0.0593
42.7	0.00384	6,370	0.0364	35.7	0.00295	4,830	0.0513
56.9	0.00462	7,660	0.0334	56.2	0.00406	6,660	0.0426
93.6	0.00613	10,160	0.0312	97.3	0.00571	9,300	0.0377
228.0	0.0102	16,990	0.0272	221.0	0.00894	14,610	0.0347
383.0	0.0138	22,950	0.0250	457.0	0.0134	21,700	0.0319
637.0	0.0184	30,550	0.0235	661.0	0.0168	30,200	0.0303
1254.0	0.0272	45,100	0.0212	1358.0	0.0244	39,800	0.0277
2390.0	0.0391	64,800	0.0196	2490.0	0.0340	55,600	0.0270
4740.0	0.0575	95,300	0.0179	4710.0	0.0484	79,100	0.0246
8070.0	0.0771	127,600	0.0170	7360.0	0.0621	101,600	0.0239
				9430.0	0.0717	117,300	0.0229



TABLE III CONT'D

## STEEL TUBING TEST RES.

SPECIMEN No. 9- STRAIGHT				SPECIMEN No. 9 - CORNED			
$\rho = 1.937 \frac{\text{SLUGS}}{\text{FT}^3}; \mu = 2.45 \times 10^{-6} \frac{\text{SLUGS}}{\text{FT}-\text{SEC}}$				$\rho = 1.957 \frac{\text{SLUGS}}{\text{FT}^3}; \mu = 2.27 \times 10^{-6} \frac{\text{SLUGS}}{\text{FT}-\text{SEC}}$			
$L_F$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{eNR}$	f	$A_D$ LBS/FT <sup>2</sup>	$\dot{m}_i$ SLUGS/SEC	$R_{eNR}$	f <sub>c</sub>
14.8	0.00259	3,730	0.0417	16.9	0.00227	3,500	0.0616
47.2	0.00505	7,270	0.0349	31.4	0.00351	5,420	0.0478
96.8	0.00760	10,930	0.0316	55.2	0.00516	7,970	0.0389
308.0	0.01486	21,400	0.0263	128.4	0.00828	12,810	0.0351
1220.0	0.0329	47,400	0.0212	402.0	0.0156	24,000	0.0312
4670.0	0.0695	100,000	0.0182	1284.0	0.0276	45,700	0.0275
				2310.0	0.0410	63,200	0.0258
				5590.0	0.0667	103,100	0.0235

[illegible]

TABLE III CONT'D  
STEEL TUBING TEST RESULTS

SPECIMEN No. 11 - STRAIGHT $P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.47 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$				SPECIMEN No. 11 - COILED $P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$\frac{P}{\rho} \frac{N_R}{f}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$\frac{P}{\rho} \frac{N_R}{f}$	$f$
26.4	0.00328	4,140	0.0387	15.5	0.00225	3,350	0.0625
63.0	0.00615	6,690	0.0340	28.9	0.00347	5,220	0.0490
111.3	0.00867	12,250	0.0302	54.7	0.00537	5,190	0.0367
358.0	0.0172	24,300	0.0248	126.9	0.00860	12,910	0.0350
1235.0	0.0350	47,500	0.0205	399.0	0.0162	24,300	0.0311
4620.0	0.0730	103,100	0.0178	1279.0	0.0309	46,500	0.0272
				2305.0	0.0428	14,400	0.0256
				5370.0	0.0681	112,400	0.0236
				7210.0	0.0791	119,000	0.0234

SPECIMEN No. 12 - STRAIGHT $P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.325 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$				SPECIMEN No. 12 - COILED $P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.37 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$\frac{P}{\rho} \frac{N_R}{f}$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$\frac{P}{\rho} \frac{N_R}{f}$	$f$
27.4	0.00389	5,890	0.0371	17.6	0.00216	3,210	0.0715
46.2	0.00510	7,720	0.0339	32.3	0.00362	5,410	0.0466
86.1	0.00722	10,920	0.0314	45.4	0.00474	7,080	0.0406
218.5	0.0126	19,130	0.0261	86.0	0.00676	10,100	0.0356
366.0	0.0169	25,600	0.0244	217.0	0.0108	16,120	0.0335
612.0	0.0226	34,400	0.0227	425.0	0.0160	23,850	0.0314
1175.0	0.0328	47,700	0.0208	658.0	0.0204	30,400	0.0299
2150.0	0.0465	71,570	0.0188	1261.0	0.0293	43,500	0.0277
4490.0	0.0615	105,200	0.0176	2390.0	0.0414	61,800	0.0258
6340.0	0.0838	126,800	0.0171	4300.0	0.0578	86,400	0.0242
				5670.0	0.0675	105,900	0.0234



# TABLE IV

## PLASTIC TEST RESULTS

TEST No. 1				TEST No. 2						
$P = 1.737 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.42 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.736 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.235 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$						
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$	$N_R$	$f$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$	$N_R$	$f$	$h_c$
49.8	0.00176	3,220	0.0436		50.7	0.00182	3,230	0.0621		
64.6	0.00222	3,640	0.0433		74.4	0.00247	4,380	0.0494		
82.8	0.00258	4,230	0.0418		110.6	0.00328	5,820	0.0416		
111.2	0.00307	5,010	0.0397		210.5	0.00483	8,550	0.0367		
245.0	0.00483	7,920	0.0353		474.0	0.00742	13,150	0.0348		
499.0	0.00734	12,030	0.0311		718.0	0.00927	16,450	0.0339		
622.0	0.00823	13,450	0.0310		1505.0	0.0131	24,700	0.0312		
916.0	0.01040	17,400	0.0285		3035.0	0.0206	36,600	0.0289		
1820.0	0.01552	25,500	0.0253		5480.0	0.0290	51,400	0.0264		
3616.0	0.0233	38,200	0.0223		6880.0	0.0333	59,100	0.0251		
5820.0	0.0312	51,100	0.0201							

TEST No. 3				TEST No. 4				
$P=1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.335 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P=1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.335 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$	$N_R$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$	$N_R$	$f h_c$
78.2	0.00232	3,740	0.0590	48.6	0.00104	2790	0.0729	
117.8	0.00312	5,310	0.0488	74.4	0.00218	3,675	0.0638	
224.5	0.00475	8,150	0.0404	106.1	0.00288	4,890	0.0525	
455.0	0.00689	11,680	0.0390	211.5	0.00459	7,800	0.0371	
744.0	0.0100	15,280	0.0373	494.0	0.00742	12,600	0.0365	
1465.0	0.01309	22,200	0.0347	761.0	0.00935	15,850	0.0355	
2940.0	0.0194	32,900	0.0318	1450.0	0.0132	22,500	0.0335	
5120.0	0.0266	45,200	0.0293	2430.0	0.0196	33,300	0.0309	
6540.0	0.0310	52,700	0.0276	5260.0	0.0270	45,900	0.0292	
				6670.0	0.0309	52,500	0.0283	



## TABLE IV CONT'D.

## PLASTIC TEST RESULTS

TEST No. 5				TEST No. 6			
$P=1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.335 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$				$P=1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.335 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$			
$\frac{\Delta P}{\text{LBS}/\text{FT}^2}$	$\frac{\dot{m}}{\text{SLUGS}/\text{SEC}}$	$\frac{Re}{N_R}$	$f_{he}$	$\frac{\Delta P}{\text{LBS}/\text{FT}^2}$	$\frac{\dot{m}}{\text{SLUGS}/\text{SEC}}$	$\frac{Re}{N_R}$	$f_{he}$
76.5	0.00210	3,565	0.0705	158.4	0.00264	4,480	0.0809
113.4	0.00282	4,710	0.0580	221.0	0.00424	7,200	0.0500
203.0	0.00420	7,130	0.0468	537.0	0.00701	11,910	0.0443
448.0	0.00675	11,460	0.0400	800.0	0.00884	15,020	0.0416
752.0	0.00896	15,210	0.0380	1475.0	0.0126	21,460	0.0375
1480.0	0.0130	22,100	0.0356	2757.0	0.0183	31,100	0.0358
2950.0	0.0192	32,500	0.0327	5300.0	0.0254	43,000	0.0336
5250.0	0.0264	44,800	0.0306	6725.0	0.0290	49,200	0.0325
6690.0	0.0302	51,300	0.0298				

TEST No. 7				TEST No. 8			
$P=1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.29 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$				$P=1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.29 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$			
$\frac{\Delta P}{\text{LBS}/\text{FT}^2}$	$\frac{\dot{m}}{\text{SLUGS}/\text{SEC}}$	$\frac{Re}{N_R}$	$f_{he}$	$\frac{\Delta P}{\text{LBS}/\text{FT}^2}$	$\frac{\dot{m}}{\text{SLUGS}/\text{SEC}}$	$\frac{Re}{N_R}$	$f_{he}$
14.4	0.00103	1,791	0.0907	17.0	0.00111	1,923	0.0934
32.9	0.00190	3,280	0.0621	38.9	0.00208	3,610	0.0607
44.5	0.00240	4,140	0.0526	49.4	0.00244	4,220	0.0564
60.6	0.00302	5,240	0.0450	62.4	0.00291	5,040	0.0499
115.1	0.00451	7,800	0.0385	116.9	0.00448	7,750	0.0395
255.0	0.00689	11,710	0.0365	215.0	0.00689	11,910	0.0380
464.0	0.00946	16,380	0.0352	411.0	0.00926	16,610	0.0366
721.0	0.0121	20,900	0.0336	734.0	0.0119	20,650	0.0351
1390.0	0.0176	30,400	0.0305	1400.0	0.0171	29,500	0.0327
2130.0	0.0248	42,900	0.0291	2600.0	0.0240	41,700	0.0305
4870.0	0.0351	60,800	0.0268	4710.0	0.0336	58,000	0.0284
6450.0	0.0412	71,400	0.0258	6410.0	0.0401	69,400	0.0271

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TABLE IV CONT'D

PLASTIC TEST RESULTS

TEST No. 9				TEST No. 10			
$P = 1.737 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.29 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$				$P = 1.737 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.29 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$			
$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$ $N_R$	$f h_c$	$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$ $N_R$	$f h_c$
20.3	0.00124	2,140	0.0900	21.1	0.00124	2,140	0.0937
42.4	0.00209	3,620	0.0659	45.9	0.00215	3,730	0.0672
52.5	0.00250	4,320	0.0571	57.9	0.00253	4,380	0.0613
72.1	0.00312	5,400	0.0504	77.5	0.00316	5,470	0.0542
132.1	0.00455	7,870	0.0434	141.7	0.00467	8,070	0.0440
270.0	0.00693	12,000	0.0381	277.0	0.00673	11,610	0.0417
452.0	0.00914	15,800	0.0368	454.0	0.00889	15,400	0.0396
746.0	0.0119	20,650	0.0352	766.0	0.0119	20,600	0.0366
1400.0	0.0171	29,500	0.0326	1460.0	0.0171	29,500	0.0341
2687.0	0.0246	42,500	0.0302	2690.0	0.0241	41,700	0.0315
4675.0	0.0336	58,200	0.0280	4710.0	0.0331	57,200	0.0292
6340.0	0.0401	69,400	0.0268	6460.0	0.0396	68,500	0.0280

TEST No. 11				TEST No. 12			
$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.285 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$				$P = 1.737 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.29 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$			
$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$ $N_R$	$f h_c$	$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re$ $N_R$	$f h_c$
17.8	0.000998	1,700	0.122	14.2	0.00138	2,395	0.0757
46.4	0.00194	3,360	0.0836	31.7	0.00752	4,360	0.0506
56.9	0.00227	3,940	0.0746	39.4	0.00295	5,100	0.0457
72.0	0.00265	4,590	0.0696	50.0	0.00349	6,040	0.0417
124.8	0.00388	6,730	0.0562	100.0	0.00522	10,250	0.0373
269.0	0.00624	10,790	0.0472	225.5	0.00807	13,900	0.0351
479.0	0.00870	15,070	0.0431	443.0	0.0116	20,150	0.0323
723.0	0.0109	18,900	0.0413	690.0	0.0149	25,700	0.0318
1430.0	0.0160	27,800	0.0379	1330.0	0.0214	37,000	0.0296
2650.0	0.0226	39,300	0.0350	2490.0	0.0305	52,300	0.0272
4770.0	0.0315	54,600	0.0326	4450.0	0.0424	73,500	0.0253
6520.0	0.0376	65,300	0.0313	6080.0	0.0508	87,800	0.0240



## TABLE IV CONT'D

## PLASTIC TEST RESULTS

TEST No. 13				TEST No. 14			
$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.29 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f_{lc}$	$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f_{lc}$
17.5	0.00156	2,700	0.0728	8.9	0.00106	1,862	0.0814
27.6	0.00215	3,720	0.0608	18.3	0.00164	2,680	0.0695
38.8	0.00273	4,800	0.0512	25.8	0.00204	3,585	0.0633
77.2	0.00444	7,690	0.0398	37.6	0.00266	4,600	0.0541
187.7	0.00714	12,340	0.0375	77.5	0.00444	7,800	0.0460
330.5	0.00961	16,750	0.0358	188.0	0.00720	12,660	0.0361
581.0	0.0132	22,900	0.0284	566.0	0.0131	23,000	0.0336
1083.0	0.0187	32,400	0.0315	1128.0	0.0193	33,900	0.0308
1995.0	0.0264	45,600	0.0292	2004.0	0.0266	46,700	0.0289
4390.0	0.0402	69,600	0.0276	4190.0	0.0405	71,300	0.0259
6040.0	0.0495	85,600	0.0250	6040.0	0.0497	87,400	0.0249

TEST No. 15				TEST No. 16			
$P = 1.937 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.285 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.22 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f_{lc}$	$\Delta p$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$R_{NR}$	$f_{lc}$
8.6	0.00089	1,540	0.112	16.7	0.00108	1,936	0.145
18.1	0.00152	2,640	0.0793	20.2	0.00147	2,630	0.0949
30.4	0.00216	3,740	0.0664	28.0	0.00184	3,300	0.0838
39.4	0.00251	4,500	0.0597	38.4	0.00230	4,120	0.0736
75.2	0.00406	7,050	0.0464	78.8	0.00381	6,820	0.0552
170.0	0.00700	12,110	0.0396	191.0	0.00663	11,800	0.0441
335.5	0.00952	16,500	0.0378	333.0	0.00893	15,960	0.0426
560.0	0.0128	22,100	0.0354	580.0	0.0124	22,300	0.0381
1150.0	0.0189	32,800	0.0328	1125.0	0.0178	31,900	0.0360
2010.0	0.0259	45,000	0.0304	2030.0	0.0249	44,600	0.0335
4260.0	0.0396	68,600	0.0276	4290.0	0.0378	67,700	0.0304
6050.0	0.0485	84,000	0.0262	6120.0	0.0467	83,500	0.0286



## TABLE IV CONT'D.

## PLASTIC TEST RESULTS

TEST No. 17				TEST No. 18			
$P = 1.736 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.24 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$
9.3	0.00135	2,370	0.0754	9.6	0.00135	2,387	0.0784
16.9	0.00206	3,630	0.0591	16.2	0.00191	3,380	0.0658
25.1	0.00250	4,740	0.0473	26.9	0.00269	4,750	0.0550
34.0	0.00347	6,120	0.0417	35.8	0.00354	6,250	0.0423
69.4	0.00527	9,310	0.0368	71.0	0.00519	9,175	0.0390
150.1	0.00871	15,390	0.0351	185.2	0.00860	15,210	0.0370
303.0	0.0116	20,300	0.0337	315.5	0.01153	20,430	0.0349
550.0	0.0163	28,600	0.0308	547.5	0.01578	27,900	0.0324
1036.0	0.0228	40,100	0.0296	1057.0	0.0226	39,980	0.0306
1780.0	0.0320	56,400	0.0272	1895.0	0.0314	55,500	0.0284
4120.0	0.0501	88,400	0.0242	4135.0	0.0505	89,200	0.0240
5630.0	0.0598	105,500	0.0232	5710.0	0.0590	104,200	0.0243

TEST No. 19				TEST No. 20			
$P = 1.736 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P = 1.736 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu = 2.22 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$
9.5	0.00125	2,200	0.0900	11.7	0.00115	2,050	0.131
16.2	0.00186	3,270	0.0693	18.2	0.00182	2,960	0.0971
27.6	0.00277	4,870	0.0532	26.9	0.00255	4,540	0.0611
35.8	0.00355	5,890	0.0473	36.8	0.00317	5,650	0.0542
69.9	0.00511	9,000	0.0396	73.0	0.00502	8,950	0.0427
191.5	0.00875	15,400	0.0370	189.3	0.00854	15,200	0.0384
315.5	0.0116	20,400	0.0346	312.5	0.0113	20,050	0.0364
536.0	0.0156	27,350	0.0328	527.0	0.0150	26,800	0.0344
1044.0	0.0225	39,600	0.0306	1010.0	0.0222	39,550	0.0318
1907.0	0.0316	55,600	0.0282	1923.0	0.0311	55,400	0.0294
4160.0	0.0496	87,400	0.0249	4205.0	0.0463	86,000	0.0267
5720.0	0.0595	104,700	0.0240	5720.0	0.0579	103,000	0.0252

-32-  
TABLE IV CONT'D.

PLASTIC TEST RESULTS

TEST No. 21				TEST No. 22			
$P=1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P=1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.22 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta p$ LB/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$	$\Delta p$ LB/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$
13.0	0.00142	2,490	0.0700	5.6	0.00166	2,970	0.0694
18.9	0.00182	3,210	0.0639	9.7	0.00251	4,490	0.0502
30.0	0.00255	4,490	0.0682	12.6	0.00305	5,450	0.0442
38.4	0.00304	5,350	0.0616	25.2	0.00464	8,290	0.0384
73.8	0.00467	8,210	0.0500	47.3	0.00776	13,880	0.0366
196.0	0.00811	14,280	0.0426	111.1	0.0123	18,370	0.0345
311.0	0.0107	18,880	0.0400	215.5	0.0148	26,400	0.0328
549.0	0.0147	25,920	0.0374	386.0	0.0203	36,300	0.0306
1087.0	0.0215	37,800	0.0348	700.0	0.0283	50,600	0.0286
1925.0	0.0297	52,310	0.0322	1465.0	0.0433	77,300	0.0257
4260.0	0.0466	82,000	0.0290	3690.0	0.0735	131,200	0.0224
5810.0	0.0560	95,400	0.0274				

TEST No. 23				TEST No. 24			
$P=1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.22 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$				$P=1.936 \frac{\text{SLUGS}}{\text{FT}^3} ; \mu=2.22 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT-SEC}}$			
$\Delta p$ LB/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$	$\Delta p$ LB/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{NR}$	$f_{hc}$
4.4	0.00133	2,380	0.0811	5.3	0.00128	2,280	0.106
6.4	0.00171	3,055	0.0711	6.7	0.00168	3,000	0.0785
9.8	0.00244	4,360	0.0537	10.2	0.00234	4,190	0.0607
13.3	0.00299	5,340	0.0488	14.4	0.00308	5,510	0.0498
26.7	0.00459	8,210	0.0415	25.4	0.00454	8,130	0.0404
63.0	0.00763	13,620	0.0355	65.4	0.00759	13,510	0.0373
112.6	0.0101	18,020	0.0363	111.8	0.0102	18,180	0.0355
224.0	0.0147	26,300	0.0339	217.5	0.0146	26,220	0.0333
391.0	0.0200	35,900	0.0319	315.5	0.0180	32,200	0.0319
704.0	0.0280	50,000	0.0295	708.0	0.0283	50,600	0.0290
1462.0	0.0424	75,800	0.0267	1452.0	0.0427	76,400	0.0262
3740.0	0.0728	130,100	0.0232	3700.0	0.0733	131,000	0.0226



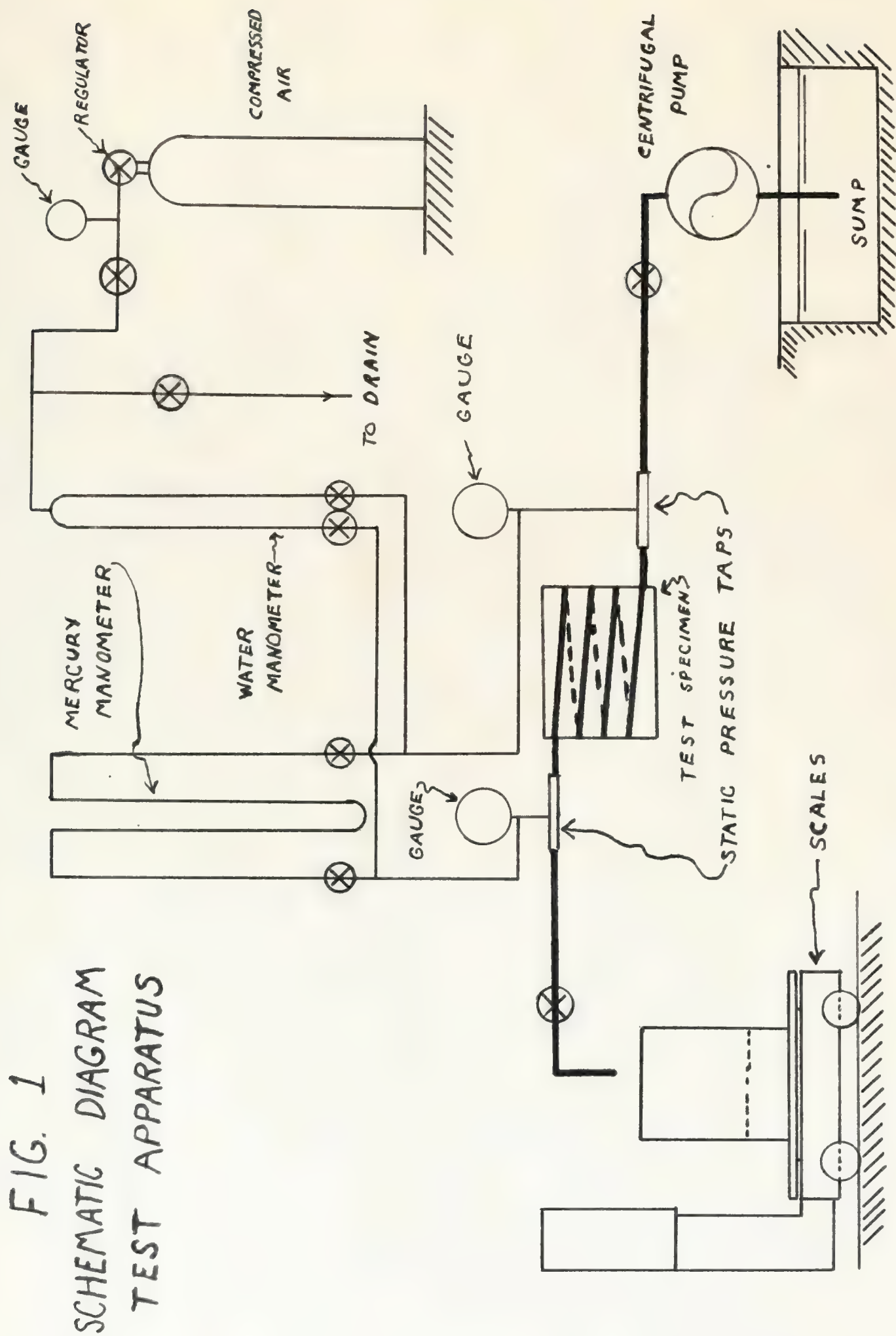
TABLE IV CONT'D  
PLASTIC TEST RESULTS

TEST No. 25				TEST No. 26			
$\rho = 1.936 \frac{\text{SLUGS}}{\text{FT}^3}; \mu = 2.25 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$				$\rho = 1.936 \frac{\text{SLUGS}}{\text{FT}^3}; \mu = 2.27 \times 10^{-5} \frac{\text{SLUGS}}{\text{FT} \cdot \text{SEC}}$			
$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{N_R}$	$f_{h,c}$	$\Delta P$ LBS/FT <sup>2</sup>	$\dot{m}$ SLUGS/SEC	$Re^{N_R}$	$f_{h,c}$
3.80	0.00108	1,900	0.107	7.6	0.00172	3,100	0.0744
7.1	0.00170	3,010	0.0801	11.1	0.00220	3,840	0.0755
9.6	0.00224	3,940	0.0637	14.6	0.00269	4,190	0.0662
14.1	0.00290	5,110	0.0547	27.8	0.00422	7,360	0.0512
26.4	0.00447	7,850	0.0434	70.8	0.00736	12,820	0.0429
63.5	0.00753	12,250	0.0367	115.3	0.00972	16,960	0.0401
111.9	0.00994	17,500	0.0371	225.0	0.0142	24,500	0.0366
220.5	0.0145	25,500	0.0344	388.5	0.0192	33,400	0.0348
382.0	0.01966	34,600	0.0323	723.0	0.0269	46,900	0.0328
701.0	0.0275	45,400	0.0304	1530.0	0.0413	72,000	0.0295
1481.0	0.0422	71,800	0.0274	3860.0	0.0705	123,000	0.0255
3830.0	0.0722	127,000	0.0241				

[illegible]



FIG. 1



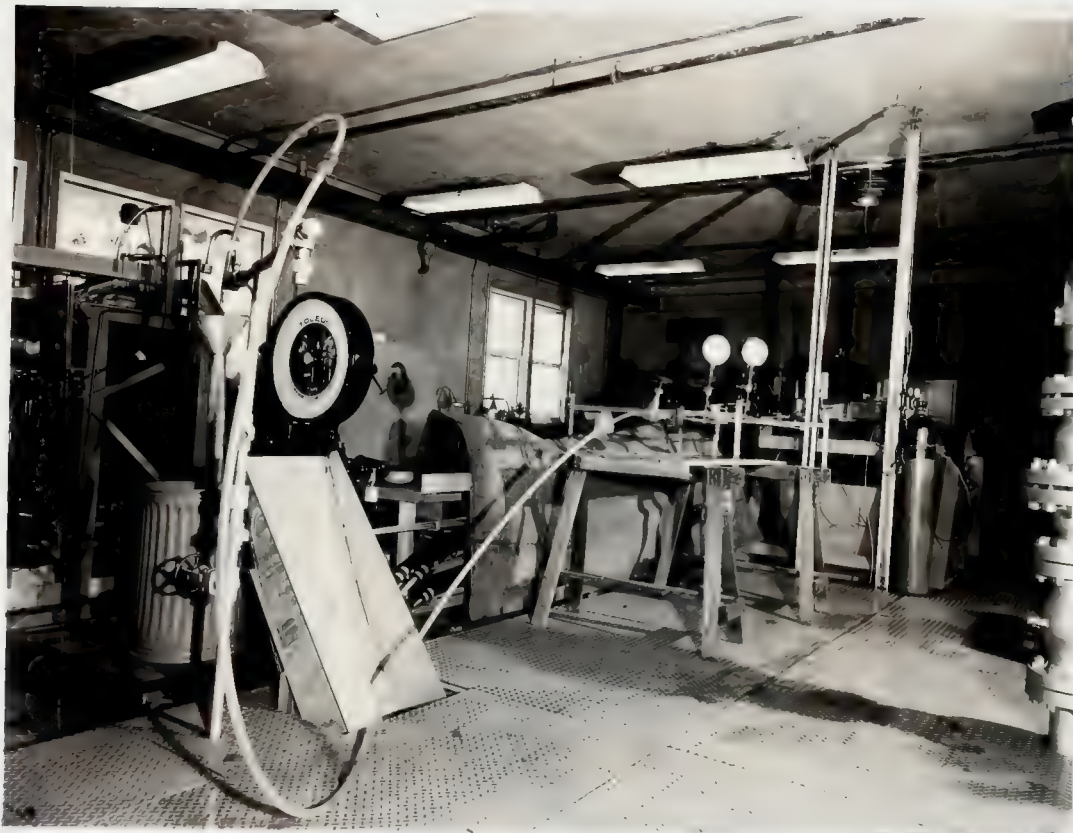


FIG 2

General Layout of Complete Apparatus

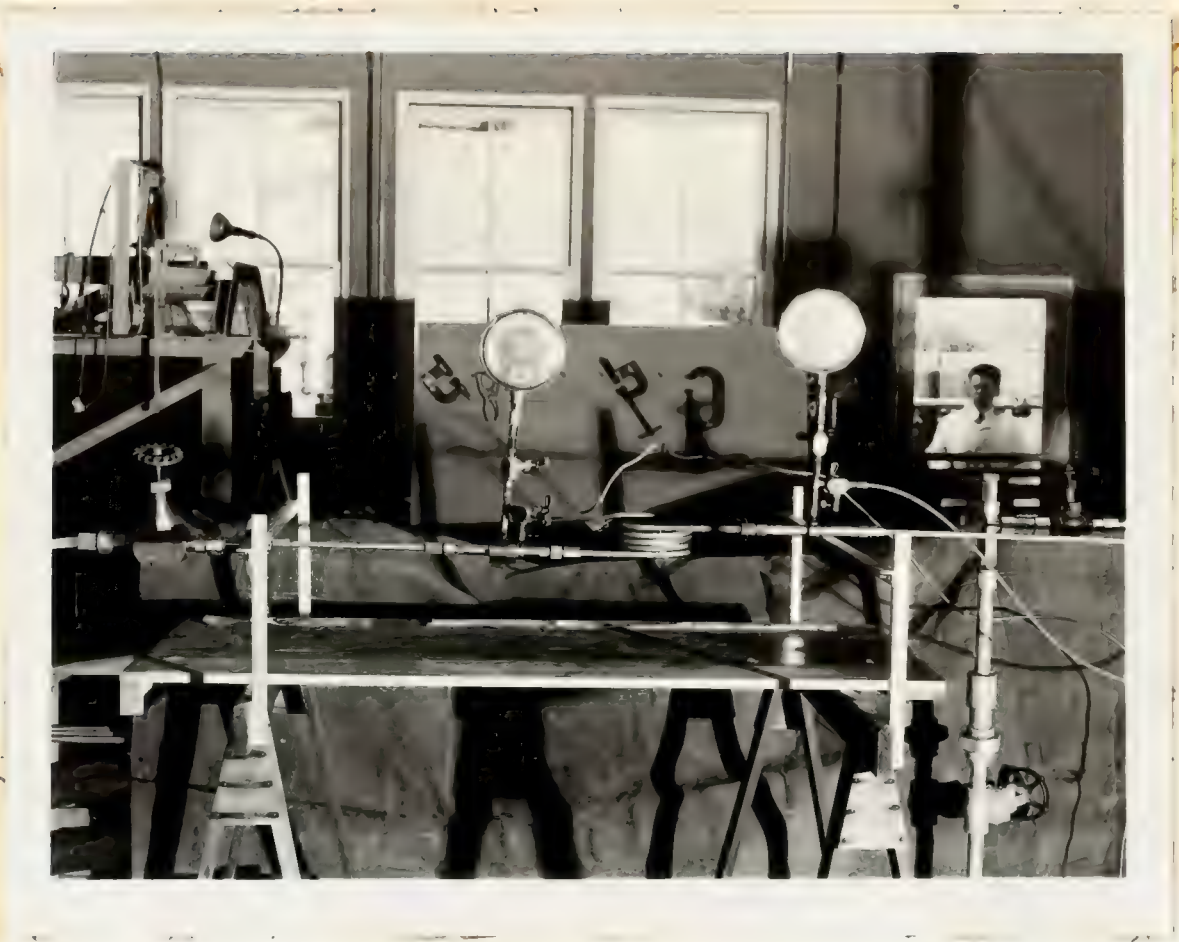


FIG 3

Steel Helix on Test Stand





FIG 4 .

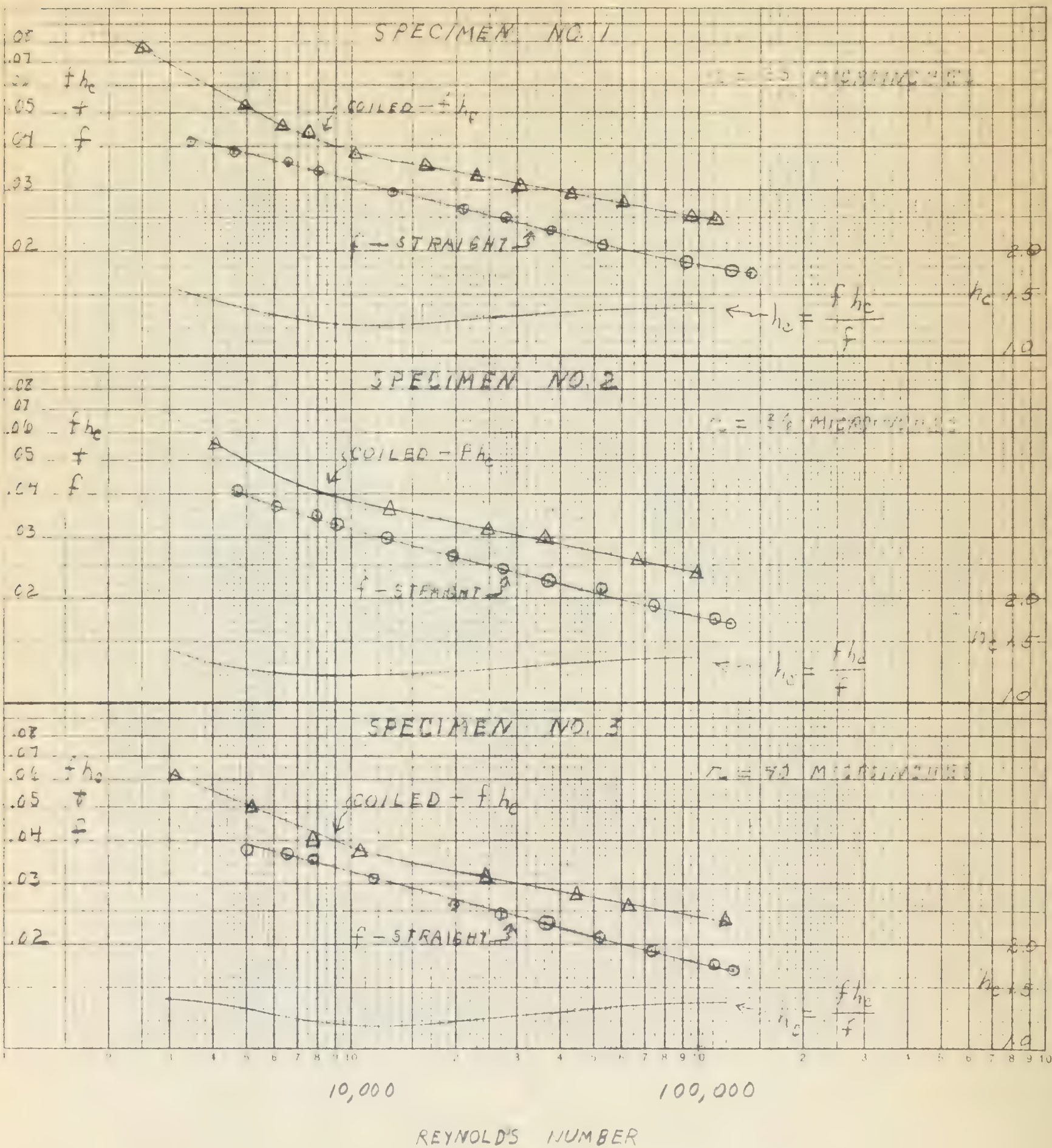
Plastic Helix on Test Stand

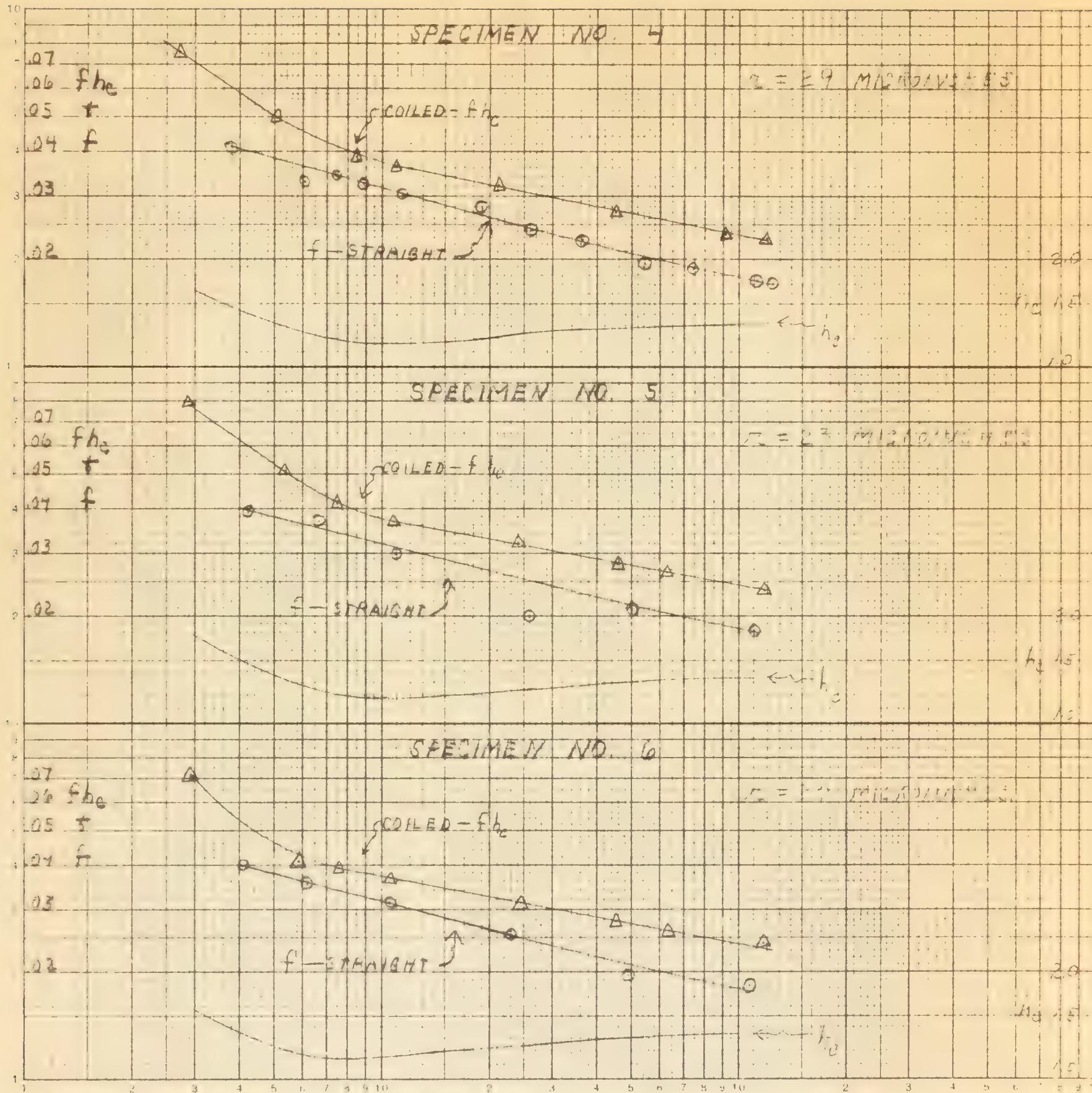


FIG 5

Forms for Plastic Helices

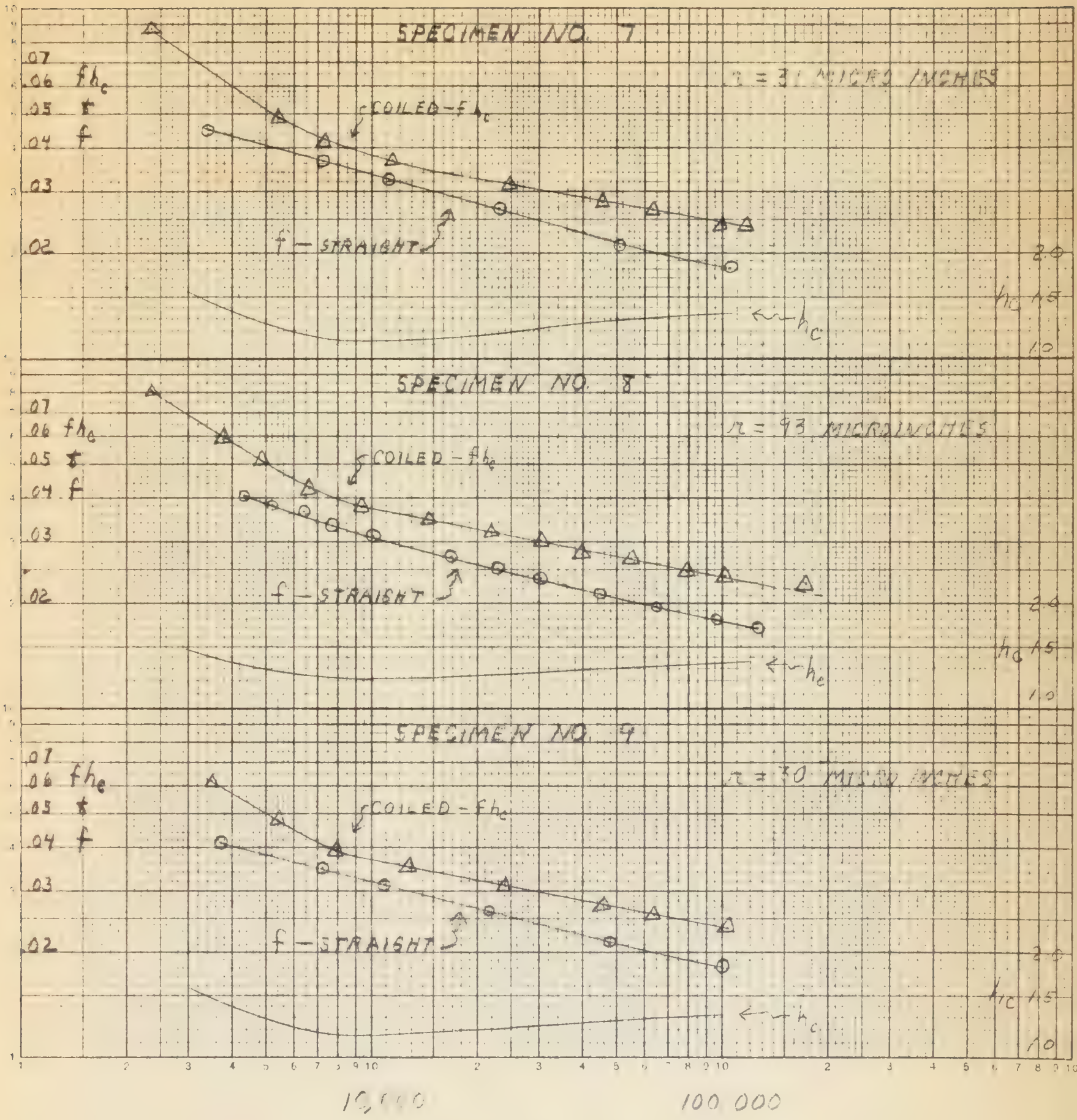






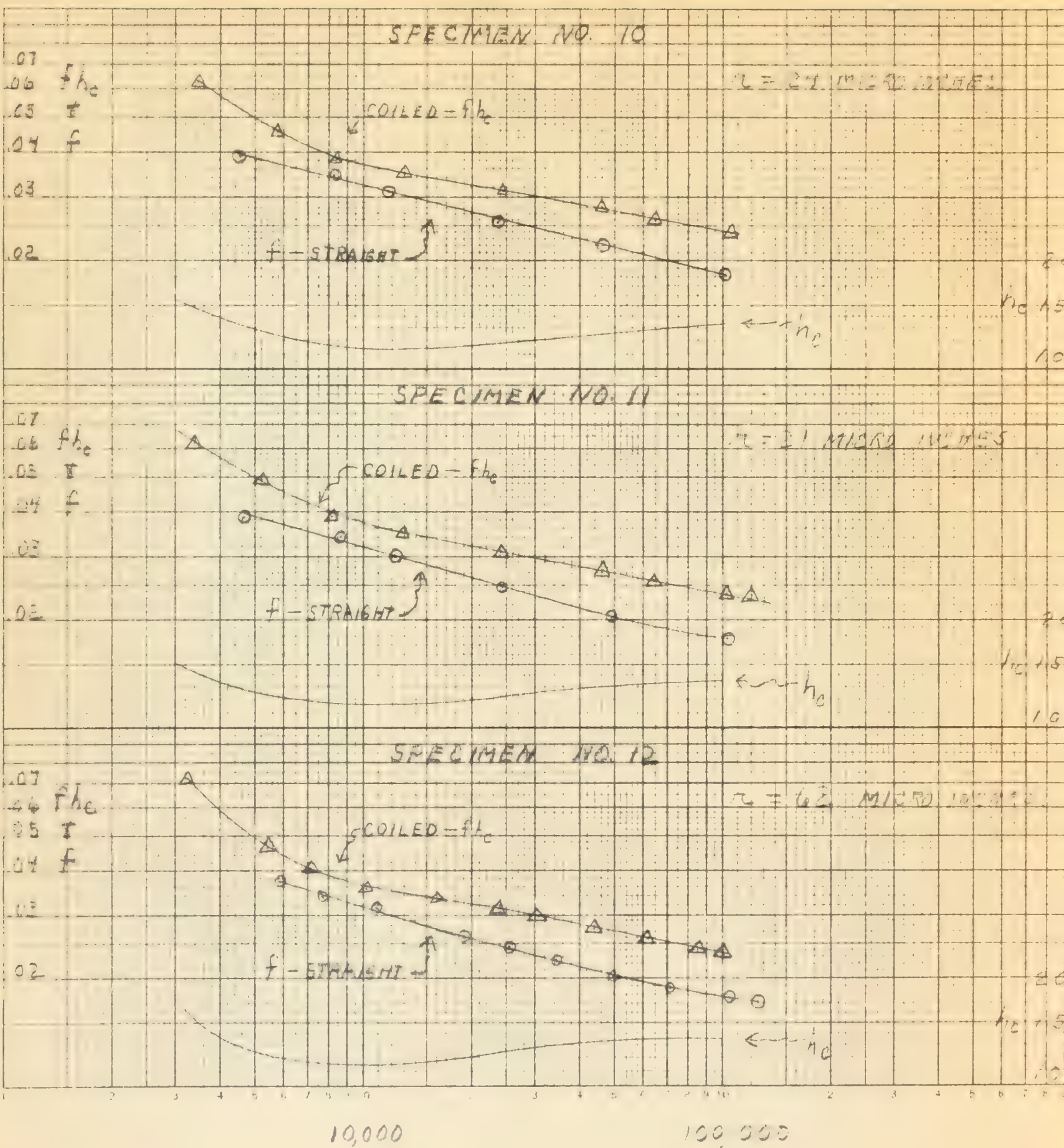


PIPE FLOW TEST RESULTS



REYNOLD'S NUMBER







# FIG. 6A

$h_c$  vs  $N_R$

STAINLESS STEEL SPECIMENS

○ SPECIMEN #1 ( $\lambda = 23 \mu m$ )

△ SPECIMEN #3 ( $\lambda = 40 \mu m$ )

□ SPECIMEN #12 ( $\lambda = 62 \mu m$ )

x SPECIMEN #8 ( $\lambda = 93 \mu m$ )

$L_{eff}(ave.) = 215.6$

$D_{eff}(ave.) = 15.53$

See Table I for exact specimen configurations.

Plotted points show source of data and not experimental points.

# FIG. 6A

2.0

1.8

$h_c$  1.6

1.4

1.2

1.0

2,000 4,000 6,000 10,000 20,000 40,000 60,000 100,000

$N_R$

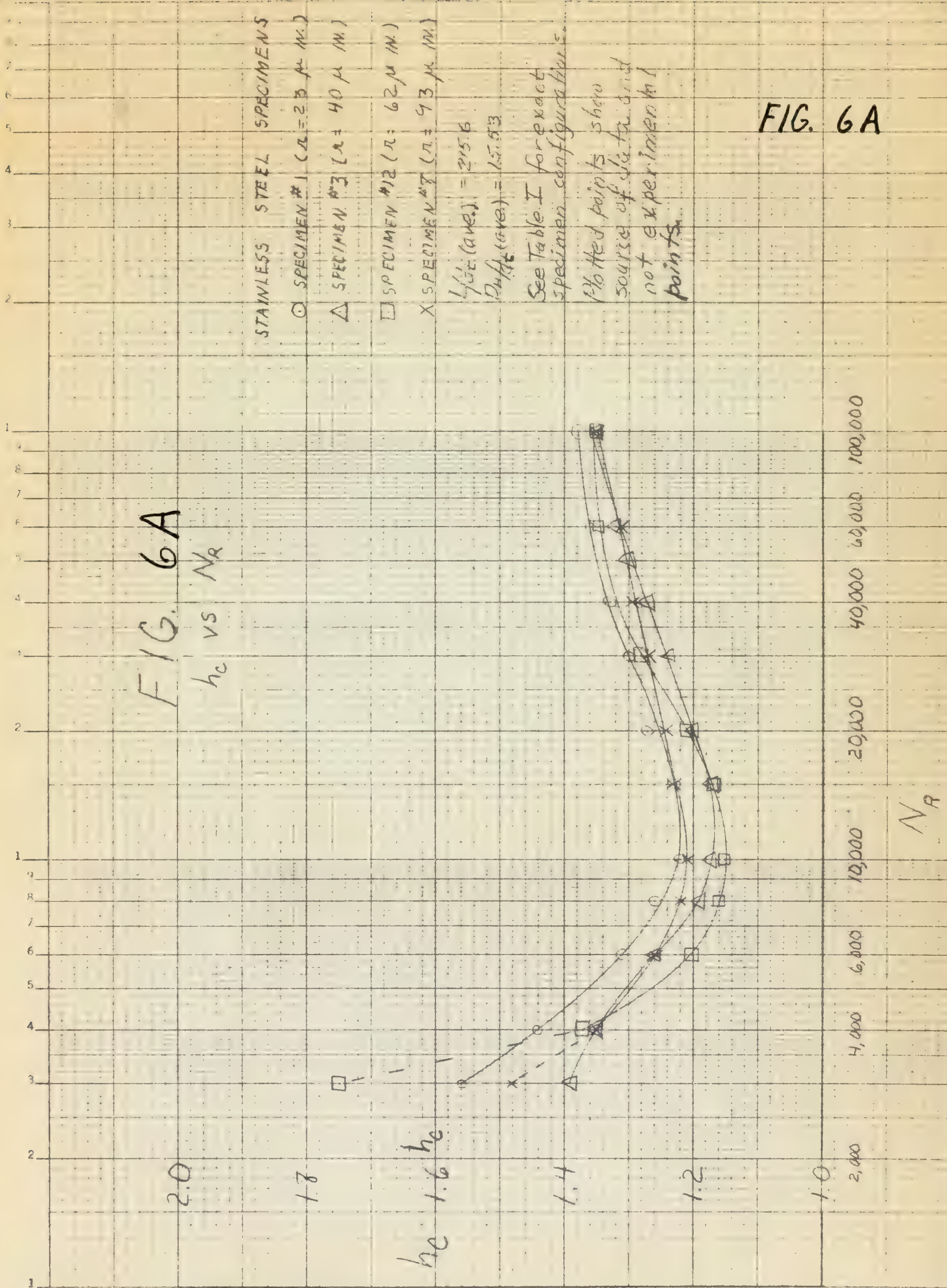




FIG. 6B

STAINLESS STEEL TEST RESULTS

Fig. 6B

$h_c$  vs.  $r/d_t$

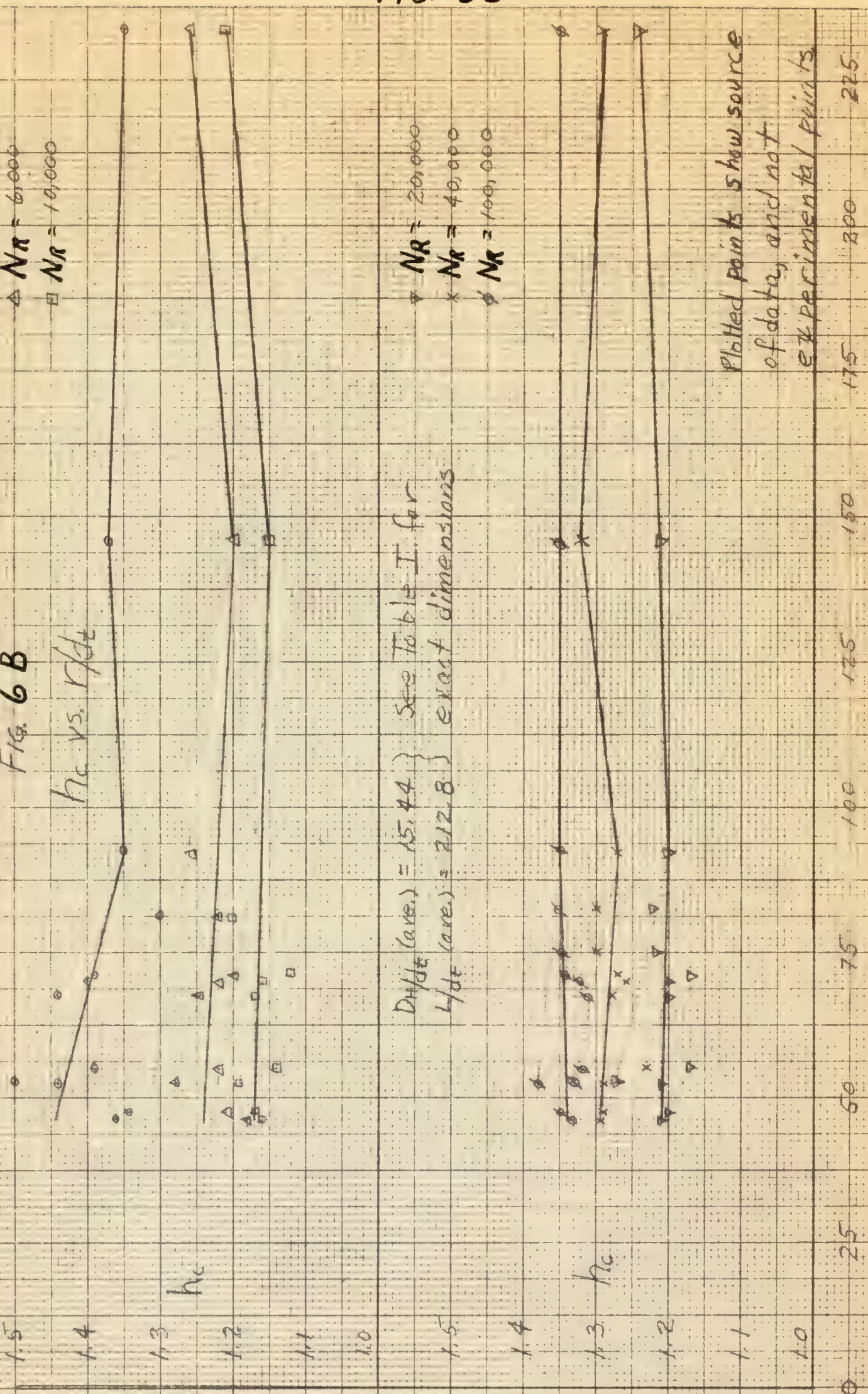
$\circ N_R = 4000$   
 $\triangle N_R = 6000$   
 $\square N_R = 10,000$

$D/d_t$  (ave.) = 15.44 } See Table I for  
 $L/d_t$  (ave.) = 212.8 } exact dimensions

$\nabla N_R = 20,000$   
 $\times N_R = 40,000$   
 $\phi N_R = 100,000$

Plotted points show source  
 of data, and not  
 experimental points

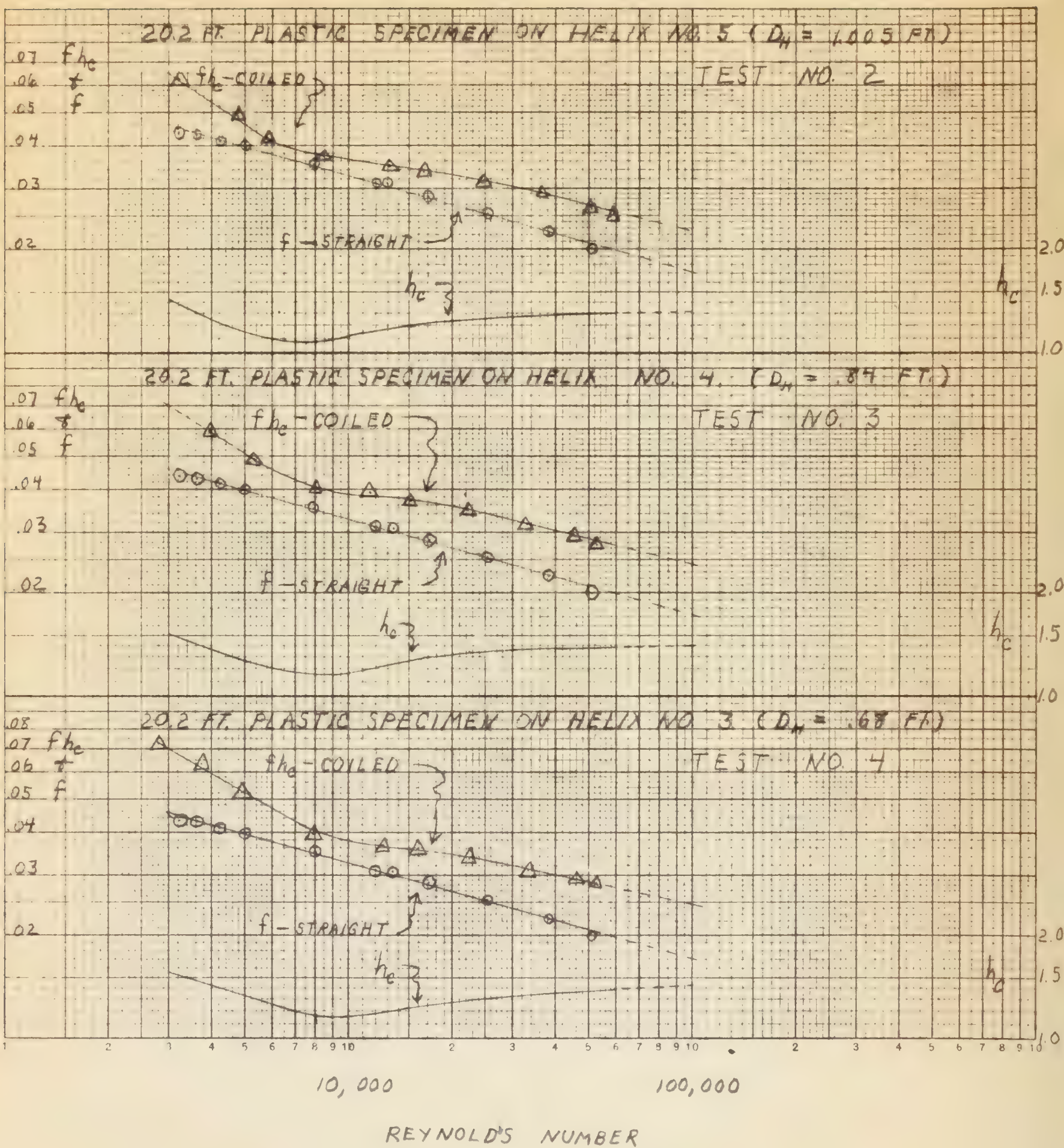
$r/d_t \times 10^6$





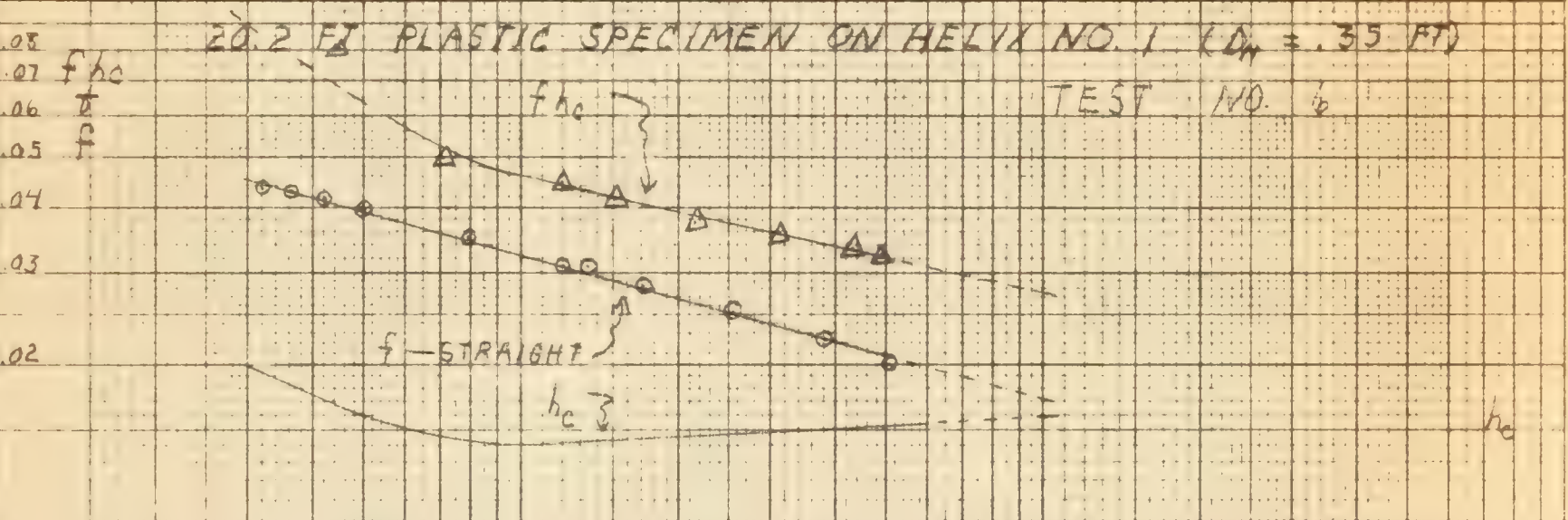
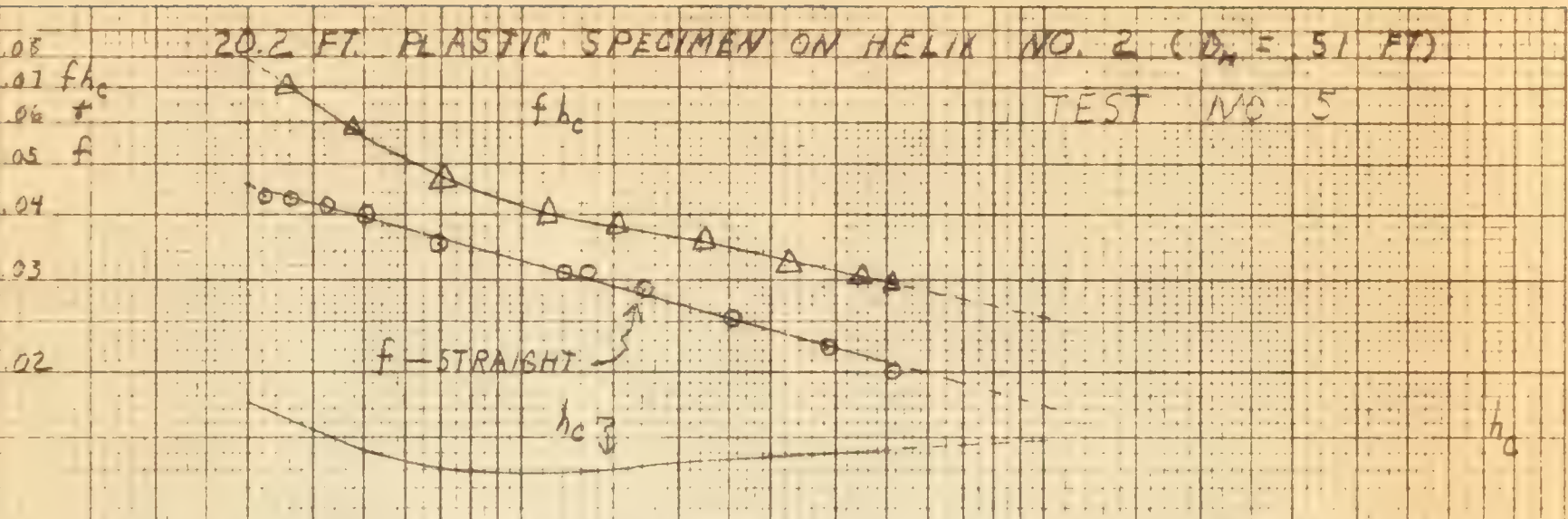
# 7

## PLASTIC TEST RESULTS





PLASTIC TEST RESULTS

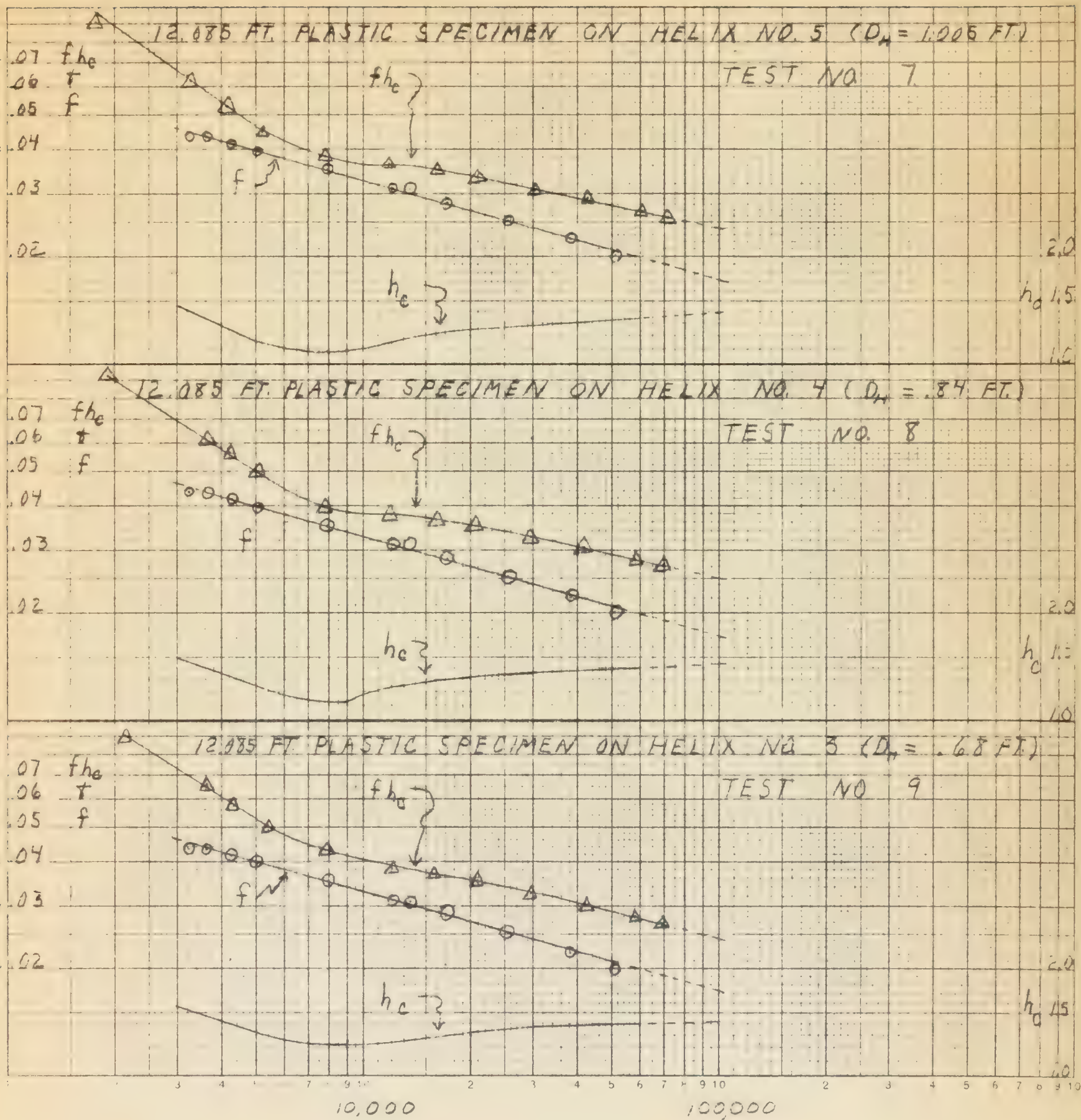


REYNOLDS NUMBER



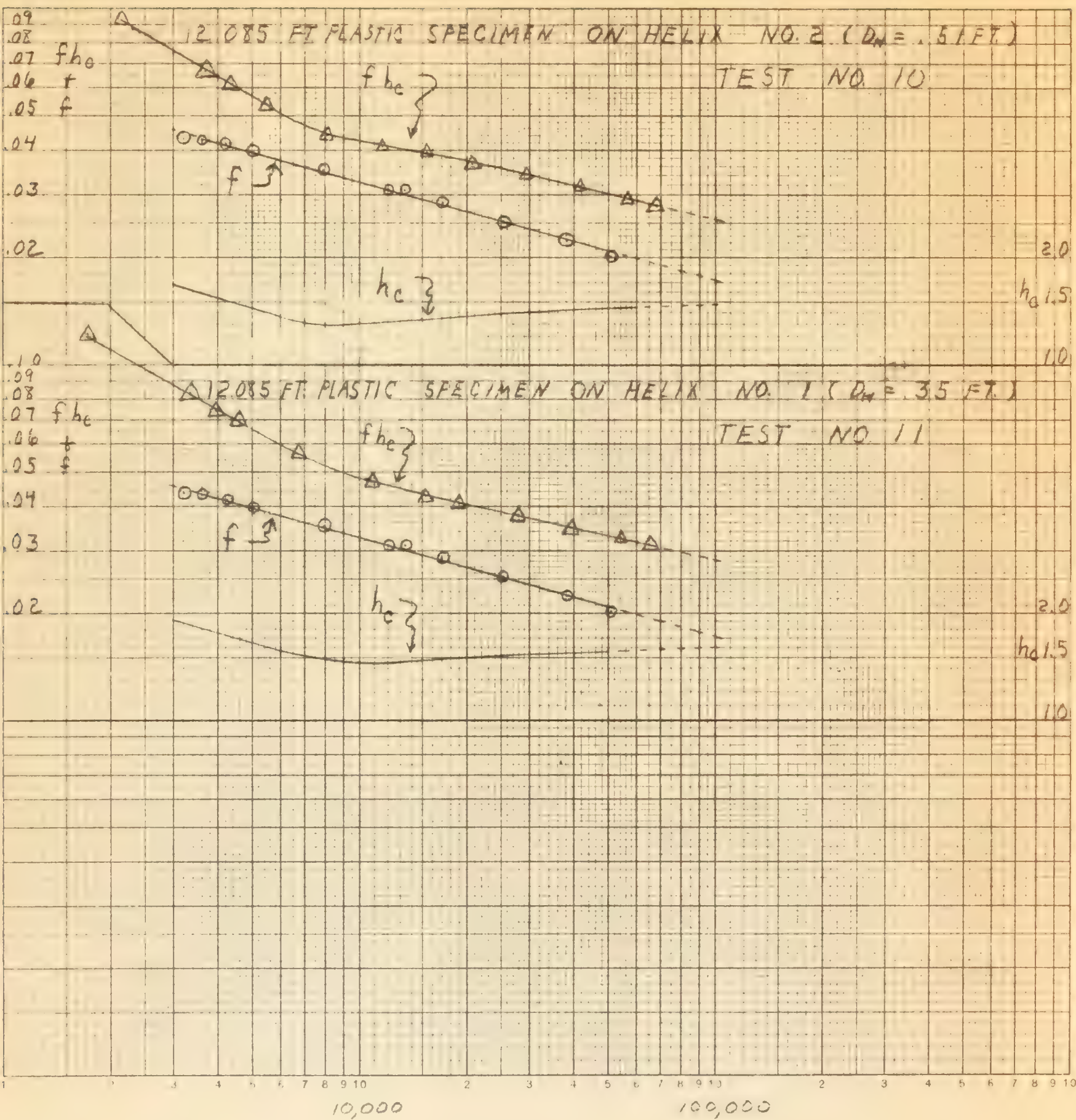
8.

PLASTIC TEST RESULTS





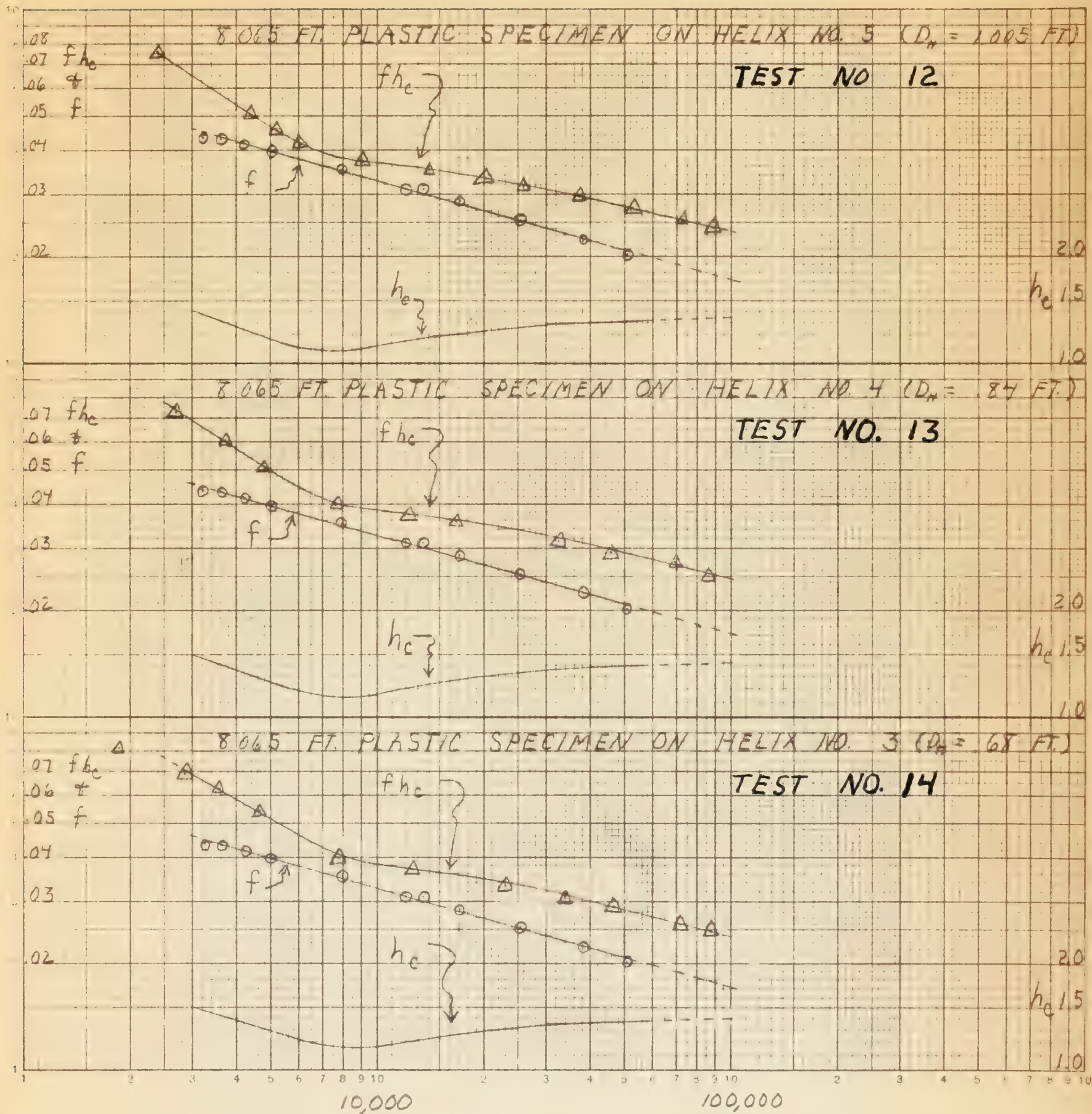
# FIG 8 CONT'D. PLASTIC TEST RESULTS



REYNOLD'S NUMBER



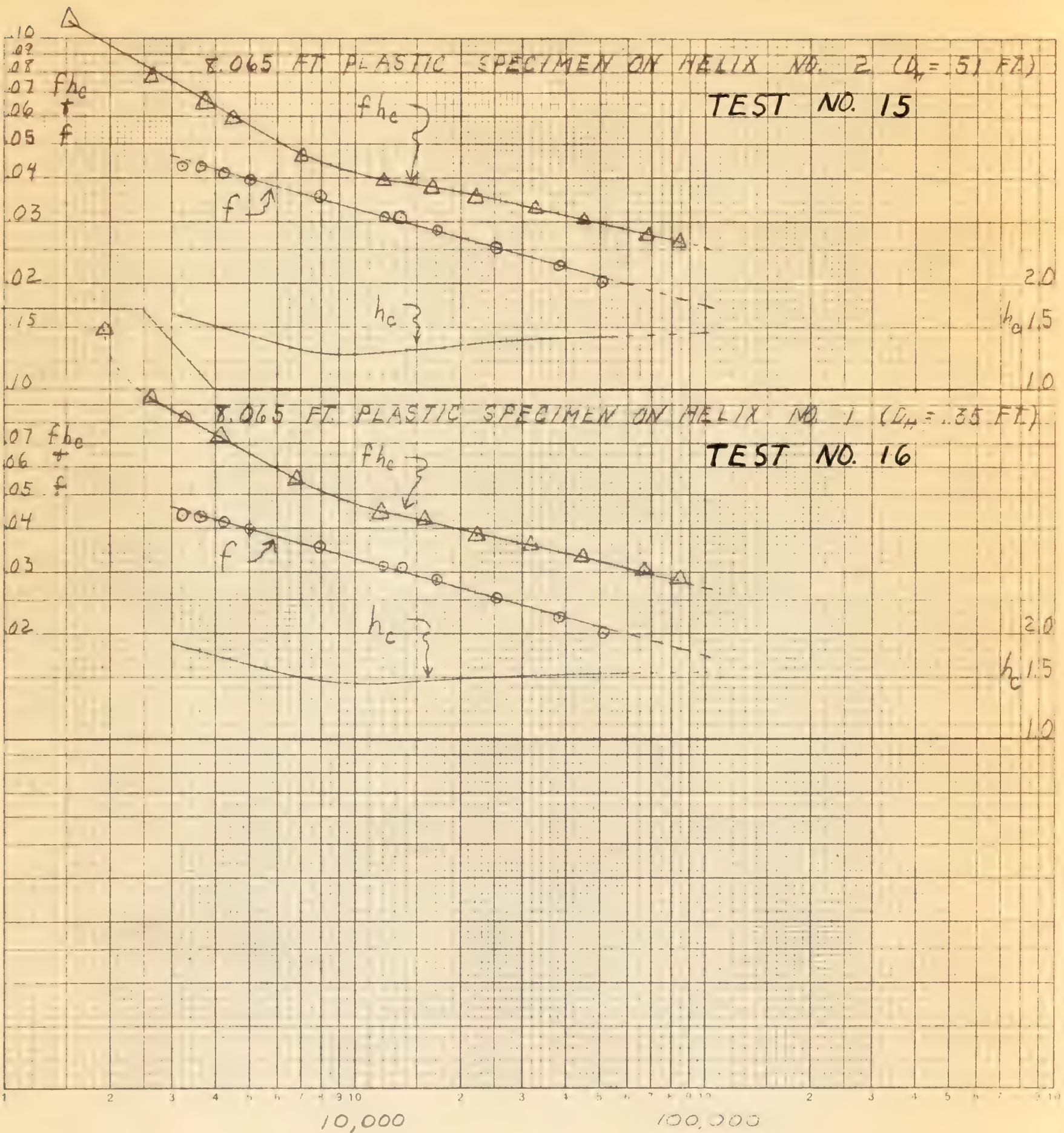
## PLASTIC TEST RESULTS



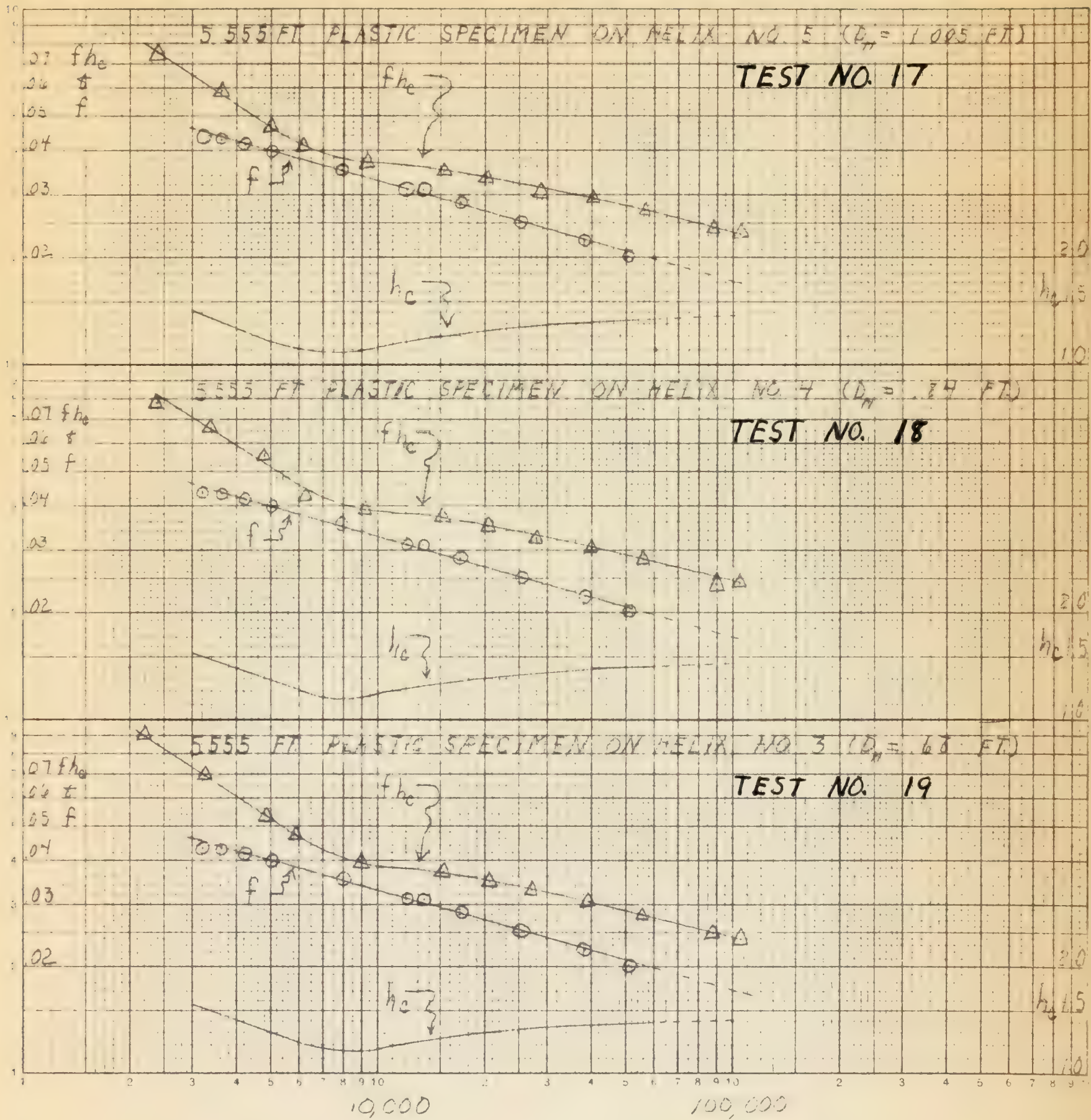


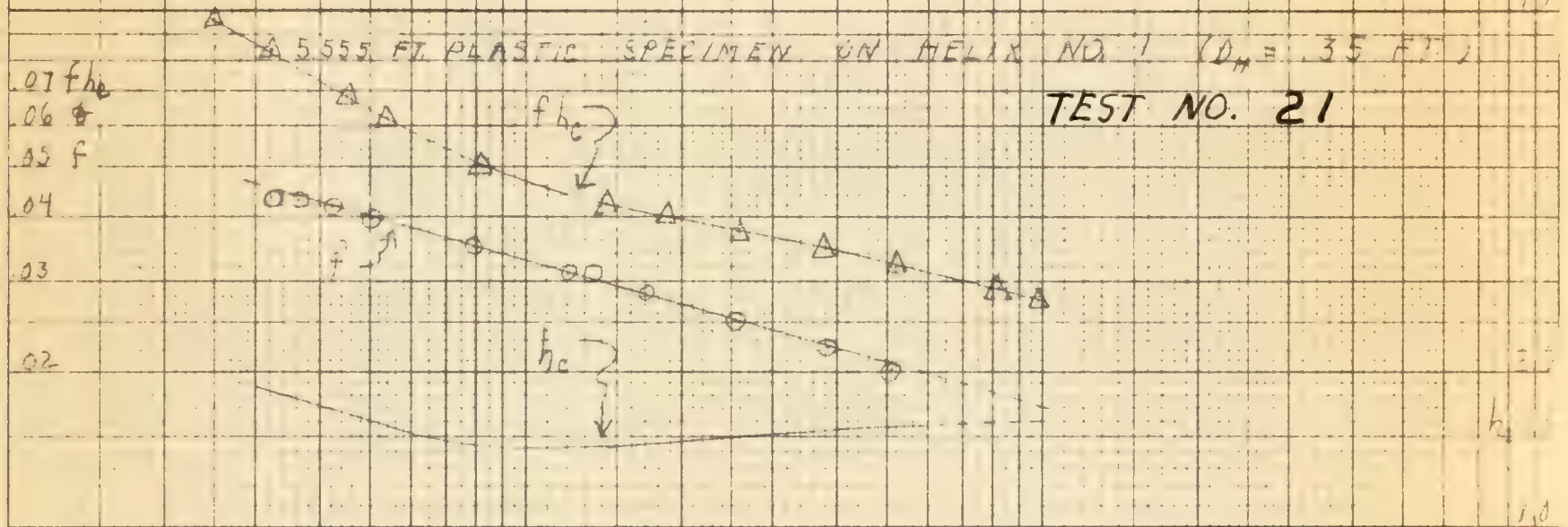
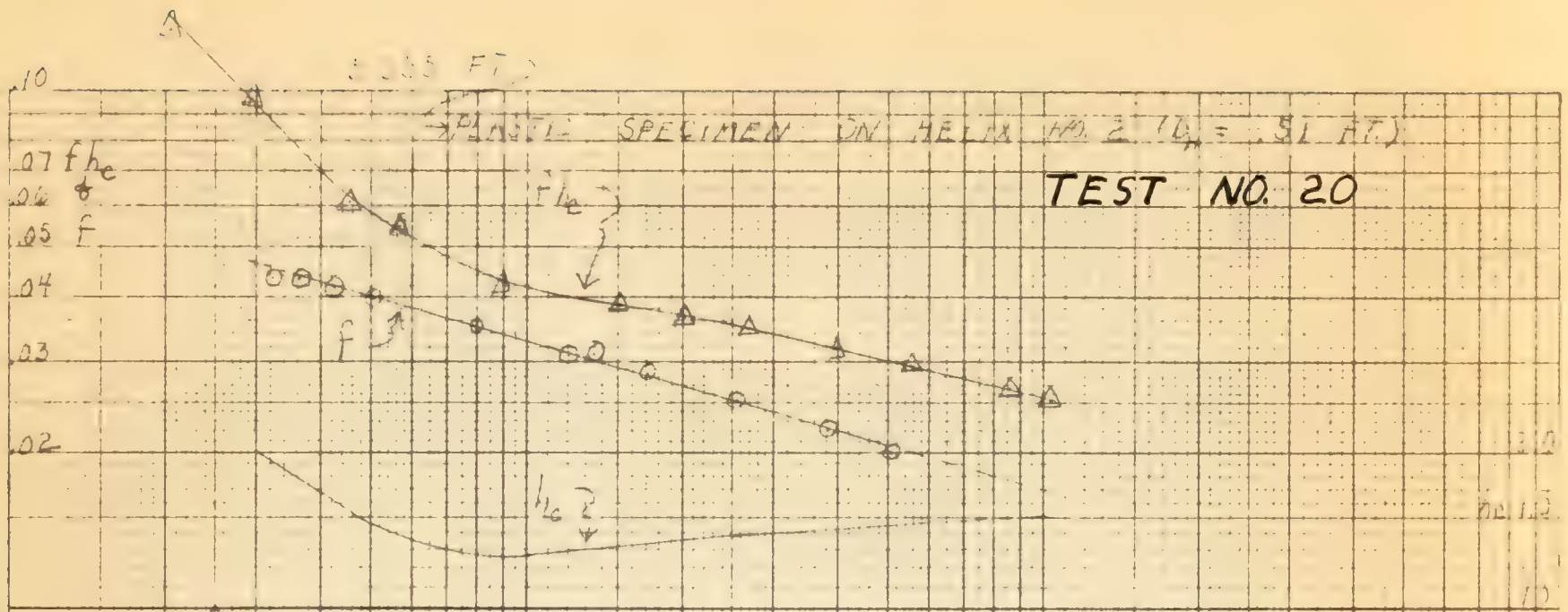
# Fig 9 CONT'D.

## PLASTIC TEST RESULTS



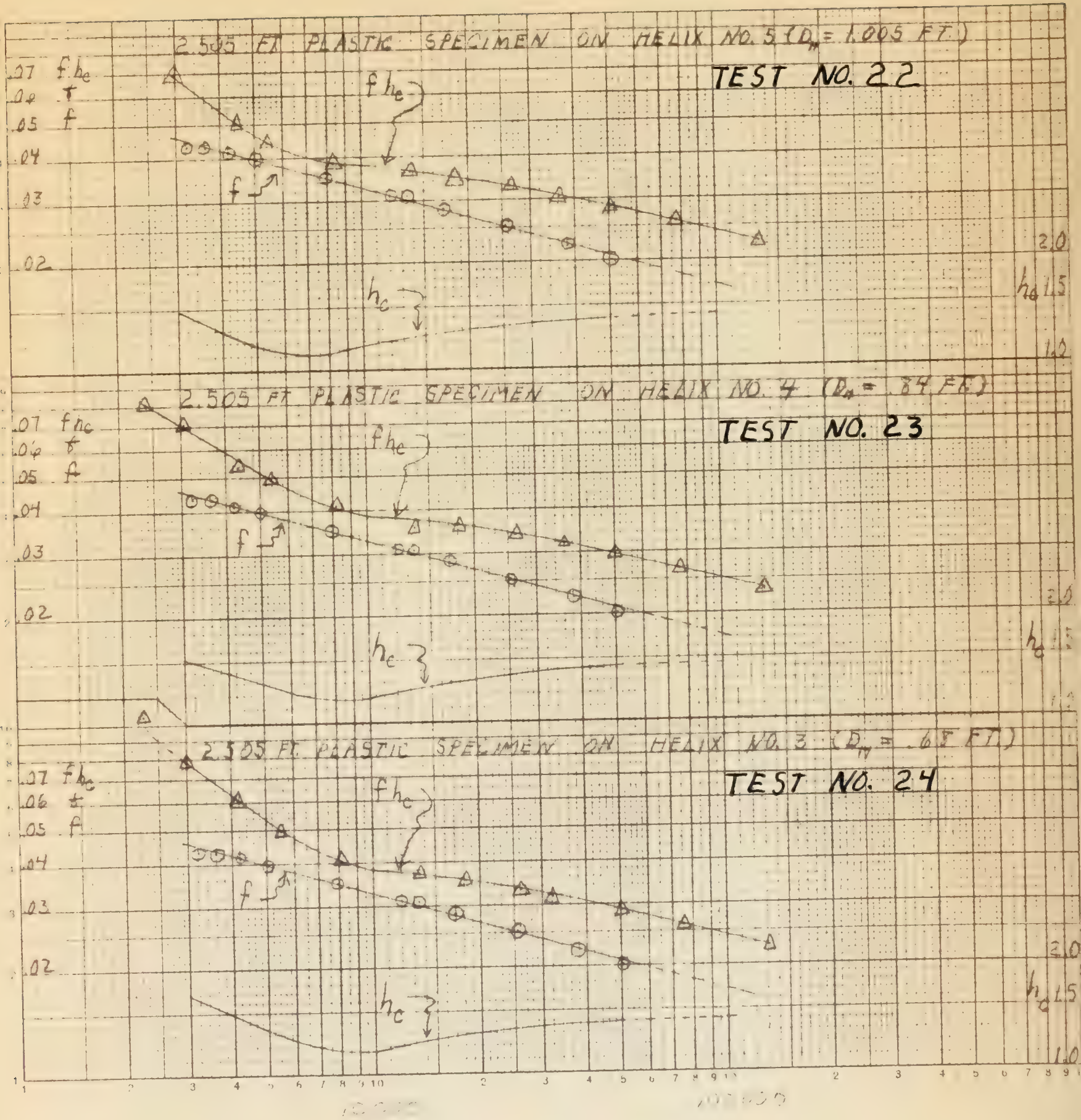








# 11 PLASTIC TEST RESULTS



REVOLVEDS NUMBER



# FIG. 11 CONT'D

## PLASTIC TEST RESULTS

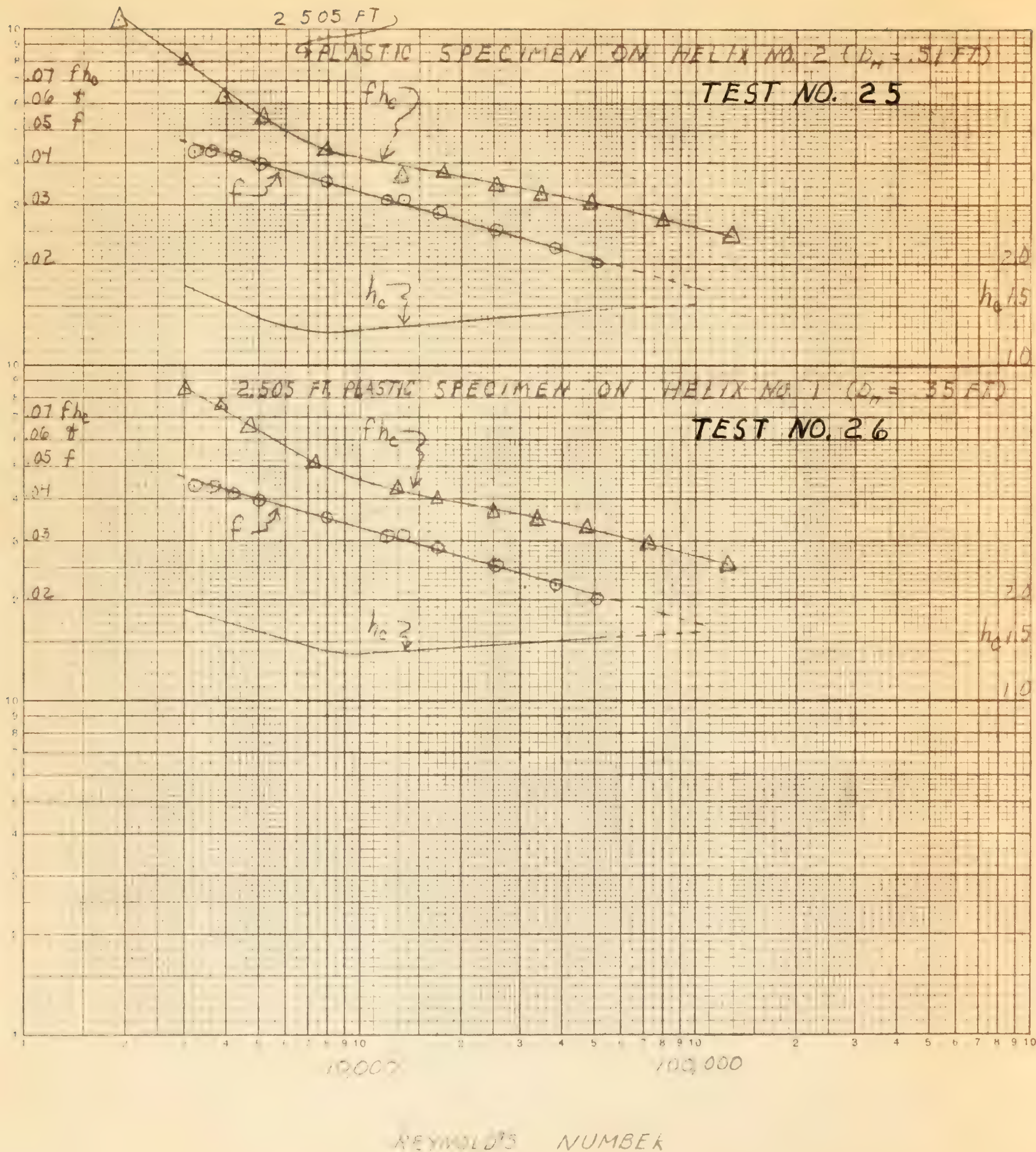
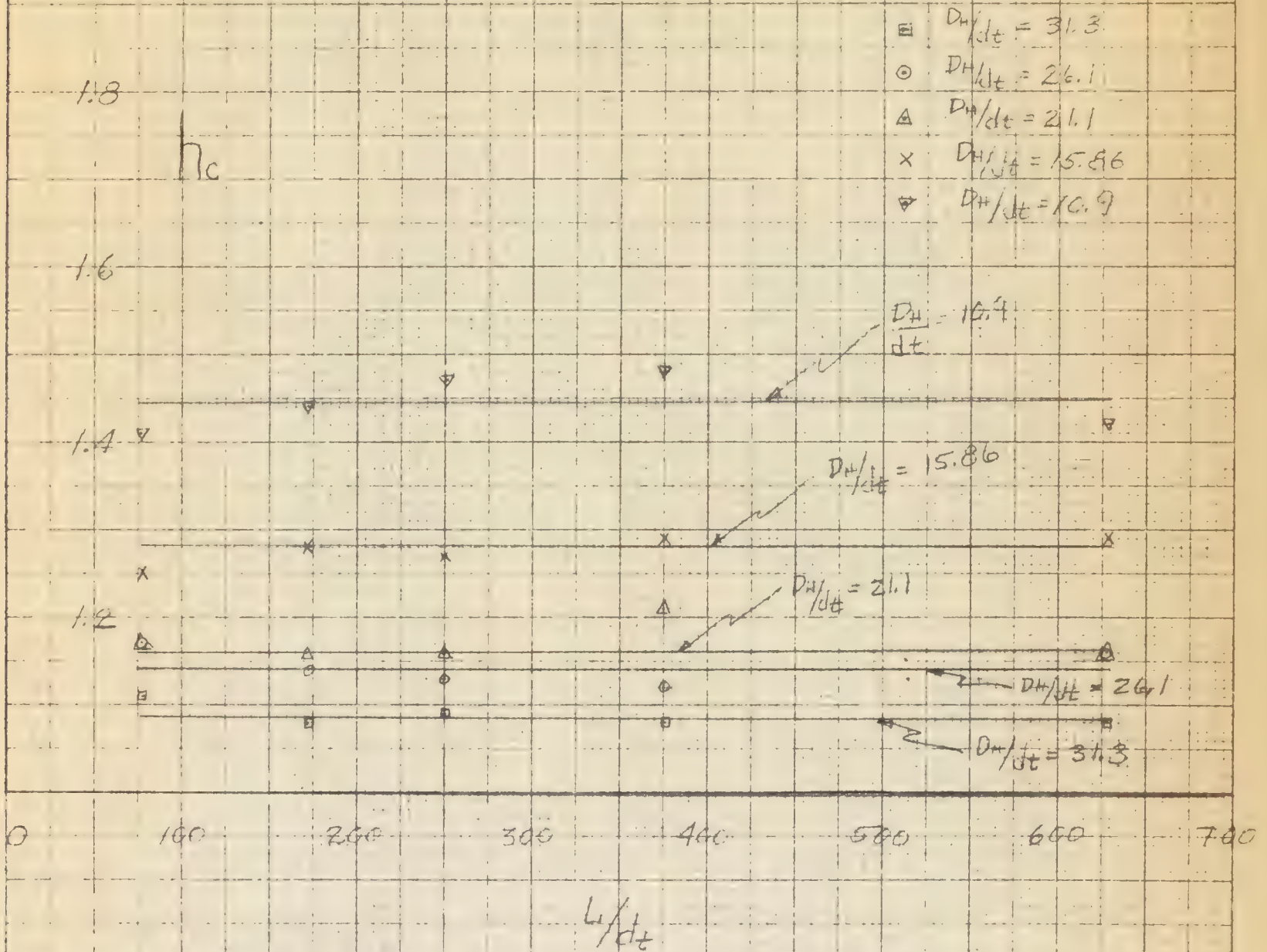




FIG. 12

$\eta_c$  vs  $L/d_t$

NR = 8,000

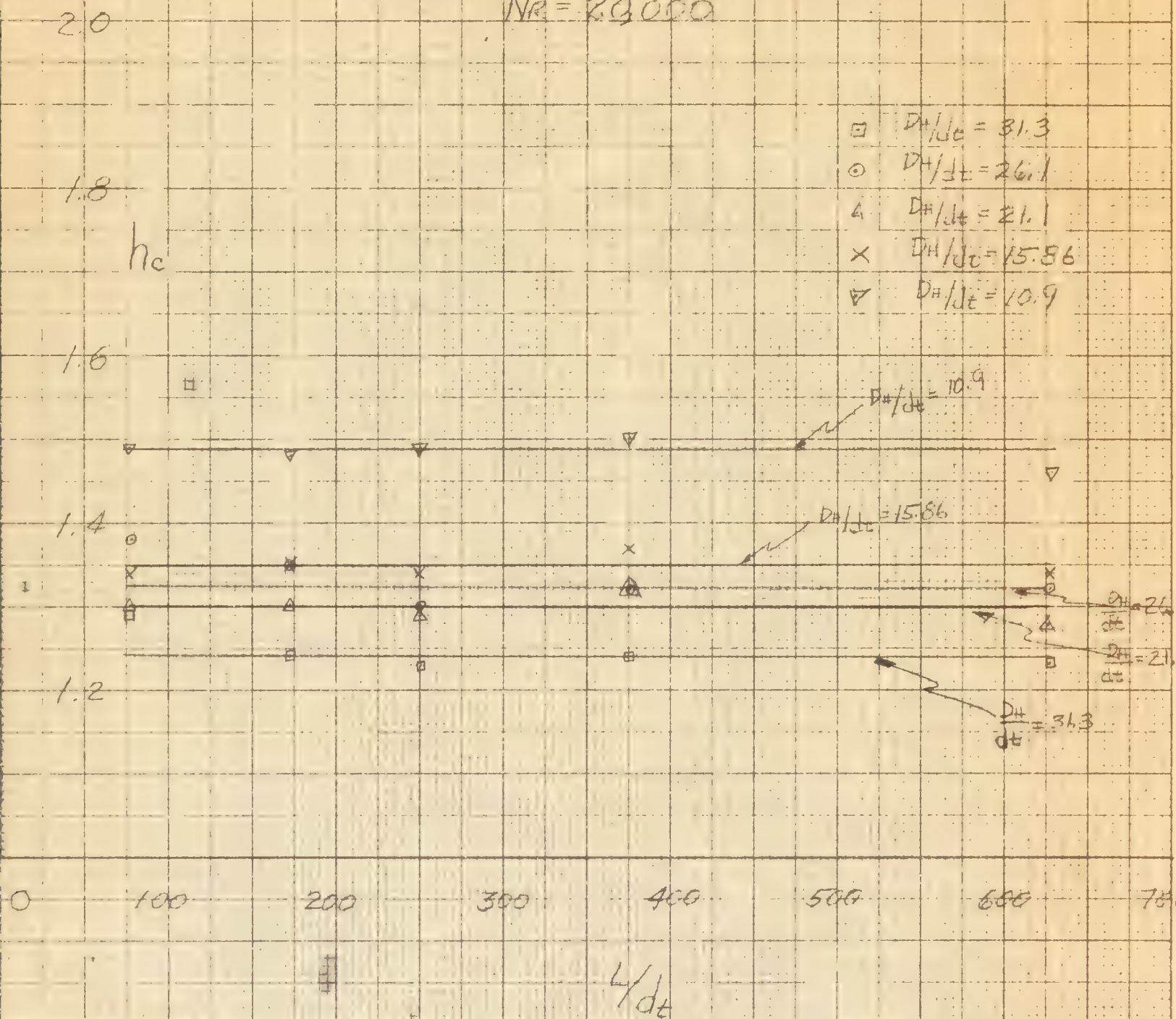


DATA FROM PLASTIC TEST RESULTS

# FIG. 13

$h_c$  vs.  $L/d_t$

$NR = 23000$



DATA FROM PLASTIC TEST RESULTS.



# FIG. 14

$h_c$  vs.  $L/dt$

$N_R = 60,000$

2.0

1.8

$h_c$

1.6

1.4

1.2

- $D_H/dt = 31.3$
- $D_H/dt = 26.1$
- △  $D_H/dt = 21.1$
- ×  $D_H/dt = 15.86$
- ▽  $D_H/dt = 10.9$

$D_H/dt = 10.9$

$D_H/dt = 15.86$

$D_H/dt = 26.1$

$D_H/dt = 21.1$

$D_H/dt = 31.3$

0 100 200 300 400 500 600 700

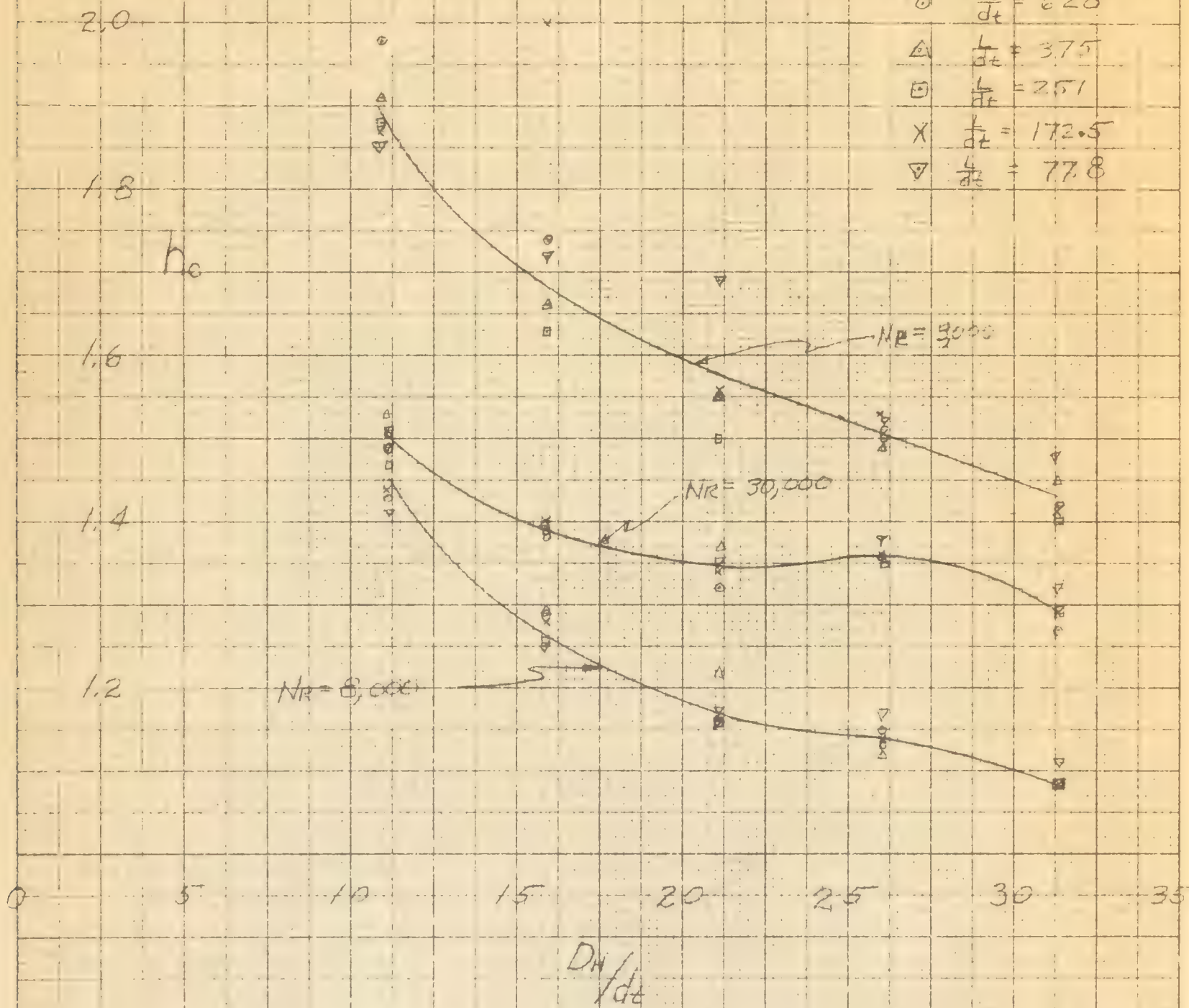
$L/dt$

DATA FROM PLASTIC TEST RESULTS

FIG. 15

$h_c$  vs.  $DW/dt$

- $\frac{L}{dt} = 628$
- △  $\frac{L}{dt} = 375$
- $\frac{L}{dt} = 251$
- X  $\frac{L}{dt} = 172.5$
- ▽  $\frac{L}{dt} = 77.8$



DATA FROM PLASTIC TEST RESULTS.



# FIG. 16

$h_c$  vs.  $DH/dt$

2.0

1.8

$h_c$

1.6

1.4

1.2

- $L/dt = 628$
- △  $L/dt = 375$
- $L/dt = 251$
- ×  $L/dt = 172.5$
- ▽  $L/dt = 77.8$

$N_R = 100,000$

$N_R = 15,000$

0 5 10 15 20 25 30 35

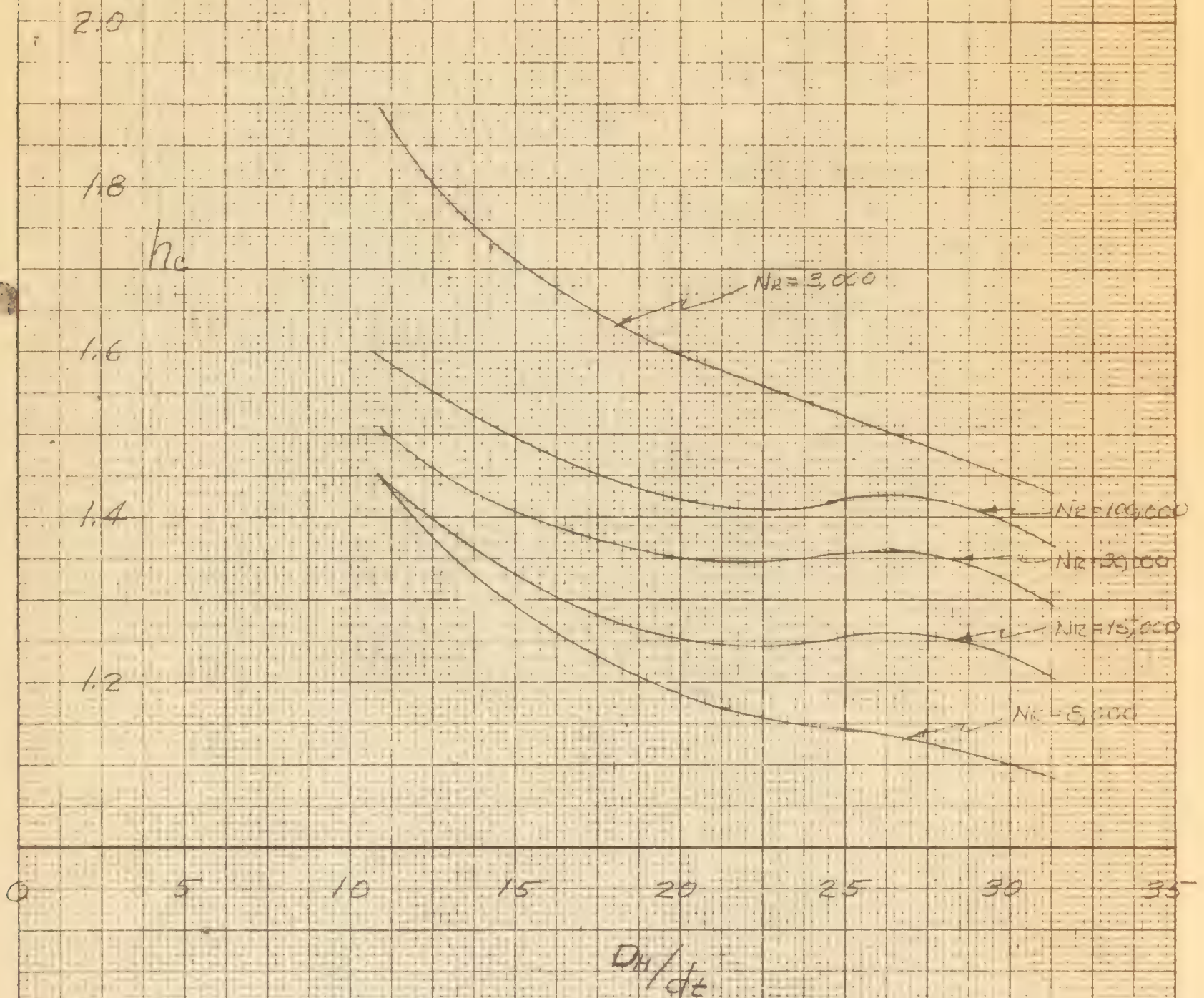
$DH/dt$

DATA FROM PLASTIC TEST RESULTS.



FIG 17

$h_c$  vs.  $DN/dt$



DATA FROM PLASTIC TEST RESULTS

THESE CURVES ARE FROM FIGS. 15 & 16.



# PLASTIC TEST RESULTS

FIG 18

$h_c$  vs.  $N_R$

$$L/d_t = 251.0$$

$$\square \quad D_H/d_t = 31.3$$

$$\circ \quad D_H/d_t = 26.1$$

$$\triangle \quad D_H/d_t = 21.1$$

$$\times \quad D_H/d_t = 15.86$$

$$\nabla \quad D_H/d_t = 10.9$$

Data for these

curves taken

for  $L/d_t = 251.0$  but

valid for all values

of  $L/d_t \geq 77.8$

Plotted points

show source of

data and not

experimental

points.

$$D_H/d_t = 10.9$$

$$D_H/d_t = 15.86$$

$$D_H/d_t = 21.1$$

$$D_H/d_t = 26.1$$

$$D_H/d_t = 31.3$$

100,000

60,000

40,000

20,000

10,000

6,000

4,000

2,000

$N_R$

2.0

1.8

1.6  $h_c$

1.4

1.2

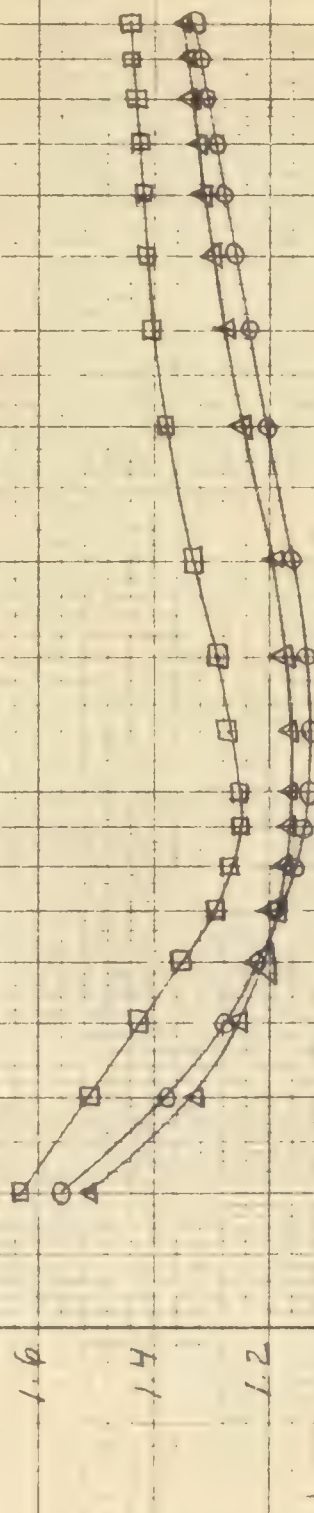
1.0



# FIG. 19

## FIG. 19

COMPARISON OF STAINLESS STEEL AND PLASTIC TEST RESULTS



○ STAINLESS STEEL SPECIMEN #10

△ STAINLESS STEEL SPECIMEN #11

□ PLASTIC TEST #15

$$\frac{D_H}{2P} = 16.25, \quad \frac{1}{P} = 2/2, \quad \frac{\tau}{D_H} = \frac{24 \times 10^{-6}}{.436} = 0.0000551$$

$$\frac{D_H}{2P} = 16.09, \quad \frac{1}{P} = 2/2, \quad \frac{\tau}{D_H} = \frac{21 \times 10^{-6}}{.437} = 0.0000480$$

$$\frac{1}{P} = 152 = \frac{2P}{7}$$

2,000 4,000 6,000 10,000 20,000 40,000 60,000 100,000

REYNOLDS NUMBER

h<sub>c</sub>



# PLASTIC TEST RESULTS FIG. 20

$h_c$  vs.  $DH/d_t$  &

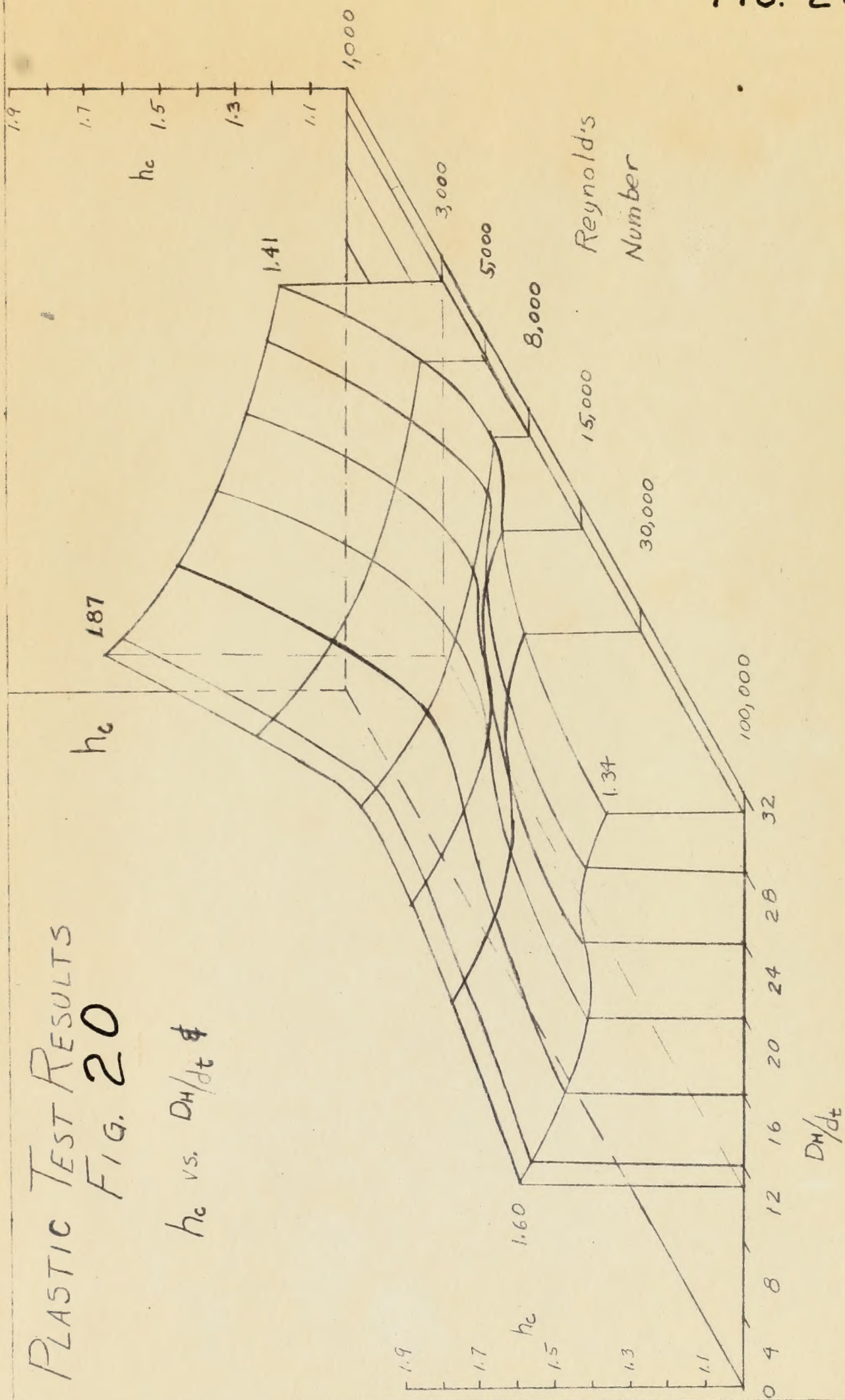


FIG. 20

## DATE DUE

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loss in flow through  
helical coils.

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